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Report No.

**PRELIMINARY INVESTIGATIONS OF
BIOFOULING OF SHIPS' HULLS:
NON-INDIGENOUS SPECIES INVESTIGATIONS
IN THE COLUMBIA RIVER**



**FINAL REPORT
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| 16. Abstract (MAXIMUM 200 WORDS) Hull biofouling is an important vector of non-indigenous species (NIS) but has received very little attention compared to ballast water. This was a preliminary examination of hull biofouling arriving to the Lower Columbia River (LCR) using three components of study. First, we examined the potential magnitude of transfers, using wetted surface area (WSA) of vessel arrivals as a proxy measure of potential colonizable surface. Second, we examined vessel hulls on drydock and by archival video footage to assess hull fouling densities. Third, we examined the existing fouling community trends and environmental 'receptiveness' of the LCR to hull mediated organisms. Over 40.5 million m ² of wetted surface area arrived to the LCR in a three year period from 66 different countries. Fouling levels on vessels examined were highly variable, ranging from less than one percent to more than ninety percent. Thirty two unique taxa (species) were found on ten drydocked vessels. Vessels that frequently traversed different salinity regimes (sea to river and vice versa) were observed to have lower levels of fouling than those which remained in either marine or riverine environments for extended periods. Overall, the threat of hull-mediated introductions to the LCR is probably not limited by propagule (organism) supply. Despite a low number of replicates, the data suggest that propagules are being delivered to the system and the cumulative surface area arriving is substantial. However, salinity and habitat availability are more likely to limit the establishment of NIS. More data are required on hull fouling densities, here and elsewhere, to answer even the basic questions regarding biofouling transfers on commercial ships. | | | |
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Executive Summary

Invasions by non-native or non-indigenous species (NIS) are a major cause of economic and ecological damage worldwide. In the marine realm, coastal ecosystems are among the most endangered in the world because invaders are altering the natural structure and function of bays and inlets where invading NIS are numerous. Shipping has long been known as a major transfer mechanism of aquatic NIS through ballast water discharge and hull fouling. Despite being identified as a potent and long-term source of organisms, hull fouling has received much less attention than ballast water. This study investigated the threat of hull fouling as a source of NIS to the Lower Columbia River.

Establishment of NIS in a new area requires introduction of organisms that are tolerant of the area conditions and that can successfully compete with native species. Factors affecting the success of NIS introductions include density, magnitude, and frequency of the release of NIS into the receiving environment. Here, we investigated the threat of NIS introductions from ships' hulls into the Lower Columbia River by examining three components: 1) the potential colonizable surface area (wetted hull) with respect to vessel type, donor region, and arrival frequency; 2) hulls of ships in drydock and by underwater video to determine extent and composition of fouling communities; and 3) the receptiveness of the Lower Columbia River and its existing bottom-dwelling communities to introduced marine organisms.

Over 40.5 million square meters (m^2) of wetted hull surface arrived in the Lower Columbia during the three-year period of July 2002 - June 2005. The monthly mean for that period was 1.12 million m^2 . Six categories of vessels were investigated, and all were potential suppliers of NIS due to biofouling on their hulls. The source of potential introductions was global – vessels arrived from 377 different ports in 66 countries with the bulk of overseas arrivals coming from Asian ports in the northwest Pacific. Total wetted hull area was dominated by bulk carriers due to their arrival frequencies, but containerships had the largest average hull area per vessel.

Drydock investigations revealed that fouling on individual vessels was highly variable (less than 1 percent to more than 90 percent). Vessels that operated solely within salt

water or within freshwater and that had not been cleaned within the last two years tended to have high levels of fouling. Vessels that commonly traversed a range of salinity conditions (such as barges that frequent the Lower Columbia) had minimal fouling.

Fouling organisms were identified to the lowest level possible – species or groups of similar species. We found 32 unique species or groups of species fouling the ships we investigated. The two most species-rich vessels arrived in the Lower Columbia from overseas, had not spent much time in freshwater prior to docking, and were fouled with organisms, many of which were probably non-indigenous to the Pacific Northwest region. Analysis of existing data about bottom-dwelling organisms and communities of the Lower Columbia and settlement panels deployed there revealed that only organisms with a wide salinity tolerance are present.

Overall this study showed that ships' hulls readily transport NIS to the Lower Columbia River, and thus NIS supply is not a limiting factor to establishment. The environmental receptiveness of the Lower Columbia, particularly the acute reduction in salinity and the limited habitat availability, is more likely to be the limiting factor. The estuarine areas near the mouth of the river are more susceptible to NIS establishment than further upriver due to 1) more ships and therefore more NIS released from hulls and ballast water, and 2) higher salinity which is more suitable for colonization by marine and brackish-tolerant organisms.

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List of Acronyms

| | |
|----------------|------------------------------------------------------|
| ABRPI | Aquatic Bioinvasion Research & Policy Institute |
| ANOSIM | Analysis of Similarities |
| ANOVA | Analysis of Variance |
| ANS | Aquatic Nuisance Species |
| BW | Ballast Water |
| CRANSI | Columbia River Aquatic Nuisance Species Initiative |
| EEZ | Exclusive Economic Zone |
| IMO | International Maritime Organization |
| IUCN | International Union for the Conservation of Nature |
| km | kilometer |
| LCR | Lower Columbia River |
| LCRANS | Lower Columbia River Aquatic Nuisance Species Survey |
| m | meter |
| m ³ | cubic meter |
| MARAD | U. S. Maritime Administration |
| MDS | Multi-dimensional Scaling |
| NBIC | National Ballast Water Information Clearinghouse |
| NIS | Non-indigenous Species |
| NW | Northwest |
| OR | Oregon |
| P | Primary |
| S | Secondary |
| SD | Standard Deviation |
| SE | Standard Error |
| TBT | Tributyltin |
| U.S. | United States |
| WA | Washington |
| WHOI | Woods Hole Oceanographic Institute |
| WSA | Wetted Surface Area |
| yr | year |

1. INTRODUCTION

This project examines the biofouling organisms associated with ships' hulls entering the Lower Columbia River (LCR) and the prospects for non-indigenous species (NIS) introduction via this mechanism. Hull fouling has been implicated in the introductions of numerous taxa throughout the world but is much understudied compared to the ballast water vector. Consequently, little is known about the current rates, extent and composition of biofouling transfers between ports. Without these data, the need for management options and their implementation cannot be critically evaluated. This study, conducted on behalf of the Columbia River Aquatic Nuisance Species Initiative (CRANSI) and funded by the U.S. Coast Guard Research and Development Center, was a preliminary examination of the hull fouling vector to the LCR taking into account shipping data, direct hull sampling, and LCR environmental factors.

1.1 Non-indigenous species

NIS are organisms of any kind that are introduced or spread outside their normal historic ranges. The increase of biological invasions by NIS worldwide is due in part to an ever-growing network of human-assisted vectors and has led to substantial ecological and economic costs. Recent events regarding the natural and human-mediated spread of avian flu have highlighted the human health concerns and the global-scale implications of bioinvasions in both popular and scientific media. Invasion biology vies with habitat loss and pollution as one of the top three causes of species extinction (depending on the systems and species examined). Thus invasion biology has become of utmost importance in the fight against threats to natural systems (Ehlich, 1988; Richter, Braun, Mendelson & Master, 1997; Wilcove, Rothstein, Dubow, Phillips & Losos, 1998).

The bioinvasion threat is almost ubiquitous on a global scale with only uninhabited and remote locations of the world uninvaded or possibly immune to invasion (*e.g.* greater than 80° latitude; Mack, Simberloff, Lonsdale, Evans, Clout, & Bazzaz, 2000). Although species introductions via human activity have increased by orders of magnitude in the last 500 years (Vermeij, 1991), data regarding the rate of introductions in recent decades is ambiguous. In the United States, rates of introductions in the past 60 years have shown

no consistent pattern (OTA, 1993). In some systems, however, the cumulative increase of introduced species detected in the last century is exponential (*e.g.* coastal invasions by invertebrates and algae; Ruiz, Fofonoff, Carlton, Wonham & Hines, 2000). The outlook for predicting future introductions is clouded by the potentially interacting effects of climate change, global commercial, technological and agricultural development, and management strategies (Reusink, Parker, Groom & Kareiva, 1995; Baskin, 1998; Dukes & Mooney, 1999; Occhipinti-Ambrogi & Savini, 2003). The consensus suggests that the potential for increased rates of introduction (and its associated costs) is high (OTA, 1993; Mack *et al.*, 2000; Pimentel, Lach, Zuniga & Morrison, 2000; Perrings, 2002).

The damage caused by NIS (or aquatic nuisance species (ANS)) is often defined in economic terms. Pimentel, Zuniga & Morrison (2005) estimated that approximately \$120 billion worth of losses are accrued by the United States (U.S.) on an annual basis due to the impact of NIS (a decrease of around \$17 billion from an estimate using the same criteria five years ago [Pimentel *et al.*, 2000]). The figure is considered an underestimate because data are unavailable, assumptions are conservative, or some issues do not lend themselves readily to dollar amounts (*e.g.* how much does a native species extinction caused by an introduction cost?). Sufficient data were available for only three aquatic invertebrates when the \$120 billion figure was calculated. This may reflect a low impact by most aquatic invertebrates in terms of economic damage, or it may highlight the shortage of information on disruption to aquatic habitats and ecosystems by invertebrate NIS. The evidence suggests the latter may be true because in North America, most established marine introductions have occurred in the fouling community and economic damage from these can be significant (*e.g.* hull maintenance and pests of the aquaculture industry).

1.2 Marine bioinvasions and vectors

The dynamics of transfer mechanisms, or vectors, remain an especially important gap in our understanding of coastal invasions, and this area of research is arguably the most important because it may lead to better ways of preventing or slowing the rate of future NIS introductions. Studies in which direct sampling of certain vectors, notably hull fouling, has been carried out are underrepresented in the literature, which has negatively

impacted predictive powers and management options. Indeed, Puth & Post (2005), in a study of the NIS literature yielding 873 papers from 23 journals during a ten year period, reported that only 11 percent of papers examined the initial introduction whereas 73 percent dealt with post-establishment issues. In addition, this analysis revealed that only 17 percent of studies were conducted in marine systems compared to 66 percent in terrestrial environments. Although analysis of vectors is increasing, the initial stage of the introduction process merits more attention, especially if resources to combat species introductions are to become proportional to the damage caused by their establishment (Pimentel et al., 2005).

Vectors of marine organisms around the world are numerous; they include biocontrol introductions, ornamental escapes, deliberate and accidental introductions associated with fisheries, canal building, and anthropogenic marine debris (Carlton, 1985; Barnes, 2002; Fofonoff, Ruiz, Steves & Carlton, 2003). The magnitude of these vectors is dwarfed by the degree to which shipping has dominated the transfer of both freshwater and marine species between bioregions (Mills, Leach, Carlton & Secor, 1993; Ruiz et al., 2000; Hewitt et al., 2004). This is unsurprising since it is a centuries-old vector of countless taxa (Carlton, 1985); recognition of ship-mediated transfers and the need for fouling prevention may have occurred as early as Greek and Roman times (Visscher, 1928; Carlton & Hodder, 1995). Ships have also dominated global trade of goods and currently transport greater than 80 percent of the world's freight. There is little doubt that shipping is the primary vector of aquatic NIS on a global scale, but the extent to which organisms have been transferred in ships (ballast water [BW]) versus on ships (hull fouling) is unknown.

Detailed investigations have shown ballast water has transferred diverse and abundant assemblages (Carlton & Geller, 1993; Smith, Wonham, McCann, Ruiz, Hines & Carlton, 1999). In one study in Coos Bay, Oregon, Carlton & Geller (1993) identified 367 different taxa arriving in ships from Japan. More recently, Minton, Verling, Miller & Ruiz (2005) have reported single ballast water release events of up to 103,000 cubic meters (m³). These discharges had theoretical propagule (organism) dosages to the receiving port ranging from 1.03×10^6 organisms (International Maritime Organization

[IMO] discharge standards) to 8.92×10^9 organisms (unmanaged BW) depending on BW management practices. Major pests of coastal and inland waterways in the U. S. are known to have been introduced and spread via ballast tanks of vessels (OTA, 1993). The factors that influence ballast water intake of organisms, survival of released organisms and major oceanic transport patterns have been studied in great detail (Carlton, 1987; Smith et al., 1999). However, work is still required on the interactive effects of density, magnitude, and frequency of BW propagule transfers on NIS establishment (Minton et al., 2005). Hull fouling, by comparison, has been largely neglected in rigorous quantitative analyses despite evidence that it may be a potent and substantial vector of organisms (Gollasch, 2002; Fofonoff et al., 2003).

1.3 Hull fouling

For North America, most established coastal marine and estuarine invasions have occurred in the fouling community and most of these have been mediated by shipping. Only 20 percent of the 316 established taxa are thought to have arrived independent of shipping (Fofonoff *et al.*, 2003). The invading organisms may have arrived on the hulls of vessels or in ballast tanks, as most have life stages that occupy both habitats. Most major taxa have been introduced, including algae, annelids, ascidians, bryozoans, cnidarians, crustaceans, diatoms, flatworms, mollusks, nematodes, protozoans and sponges (Ruiz et al., 2000; Fofonoff et al., 2003).

As a sub-vector of shipping, hull fouling is known to be a potent vector of many of these aquatic organisms. The evidence for this stems from two broad sources – inventories of NIS from certain bays and estuaries and samples taken directly from hulls. For example, Hewitt et al. (2004) suggested that hull fouling was the likely sub-vector for most (greater than 75 percent) ship-mediated invasions of Port Philip Bay, Australia. They also found that hull fouling was probably responsible for both the first and most recent introductions in the bay, although ballast water was the most likely vector for a majority of NIS introduced since 1990. In their study of 168 NIS established in the U.S., Fofonoff, et al., (2003) categorized 36 percent as resulting from hull fouling alone, whereas 20 percent were attributed to BW alone. The largest recent hull sampling study was carried out by Gollasch (2002), who recorded NIS on 96 percent of all commercial ships examined in

Germany. Godwin (2003) reported four marine NIS that were recently introduced to Hawaii via vessel hulls. Hull fouling has even ‘contributed’ taxa new to science - one species of flatworm, *Cryptostylochus hullensis* (Polycladida, Platyhelminthes) was described and is known only from hulls (Faubel & Gollasch, 1996; Minchin & Gollasch, 2003).

The potential for hull fouling to act as a dispersal vector of marine species was recognized in the mid-1800s (Darwin, 1854, as cited in Bishop, 1951) and described in detail by the early 1900s (*e.g.* Chilton, 1910; Visscher, 1928), but was first seriously considered in a global context in the mid-20th century (Bishop, 1947, 1951; Allen, 1953). Much of the early interest in hull fouling related to the impact of marine growths on vessel performance, fuel efficiency and antifouling efficiency (*e.g.* Visscher, 1928; Marine Corrosion Sub-Committee, 1944; Woods Hole Oceanographic Institute (WHOI), 1952). It is notable that current testing to determine the time of renewal for antifouling coatings is based on vessel performance and fuel efficiency rather than direct examination of biofouling accumulation (Floerl, Inglis & Marsh, 2005). In his note on the ‘distribution of marine invertebrates by ships’, Allen (1953) argued that earlier suggestions that organisms could not survive voyages attached to vessel hulls were clearly incorrect. In doing so, he brought the vector potential of ship fouling into sharp focus where the chief concern of previous work had been the negative impact on vessel speed and efficiency.

Ruiz, Miller, Everett & Steves (in prep) estimated the cumulative colonizable surface area of ships’ hulls arriving annually to U. S. ports from different biogeographic regions exceeded 400 million m². Although the potential risk of hull fouling is clear, the hull fouling vector was probably more important historically (pre-World War II) for four reasons: 1) wooden ships were the norm; 2) ship speeds were lower; 3) harbor residence times and the potential for colonization were greater; and 4) highly effective antifouling paints were unavailable. More recently, and in direct contradiction to some of these points, it has been argued that faster voyages, regulated changes in antifoulant use, improved harbor water quality, and harbor design that exacerbates hull fouling may all combine to increase the threat of hull fouling transfers (Nehring, 2001; Floerl & Inglis,

2003; Minchin & Gollasch, 2003). As is the case with ballast water, much needs to be learned about the interaction of density, magnitude, and frequency of propagule pressure from biofouling at multiple scales to allow a quantitative assessment of the threat and subsequent management of the hull fouling vector.

1.4 Biofouling adhesion, translocation and inoculation

Adhesion

Complex interactions of numerous factors contribute to the initial colonization, development, translocation and ultimate inoculation of a new area by organisms transported on vessel hulls. Sessile marine organisms are diverse and dominate hard substrata throughout the world. Their methods for attachment are also numerous, but general properties of bio-adhesion have been identified that are relevant to hull fouling. The development and succession of fouling communities on (untreated) surfaces has a general predictability; a biofilm of bacteria, diatoms, fungi, cyanophytes, algal spores and other organic material develops within hours of new space becoming available and serves as a mesh onto which subsequent fouling organisms attach (Ferguson-Wood, 1949; Henschel & Cook, 1990). As with macro-invertebrate biofouling, the extent and timing of different organisms' contribution to initial biofilm formation varies with time and space (WHOI, 1952). The development of the subsequent macro fouling assemblage was thought to require - and in some cases be stimulated by – the initial biofilm development, but there is much variability depending on the specific taxa (Henschel & Cook, 1990) and the properties of surfaces (Gray, Banta & Loeb, 2002) examined.

Translocation

Once the process of settlement and biofouling accumulation has begun on a hull, numerous factors influence the extent, composition and survivorship of assemblages. These factors in turn determine the translocation of propagules that ultimately determine whether a new area will be successfully inoculated by a NIS or population.

Hull surface area and complexity

Hull surface area affects biofouling extent and composition simply by providing the potential colonizable surface to which organisms can attach. It is analogous to ballast water discharge volumes in determining the magnitude of propagule delivery. Hull surface area has not been considered in previous studies despite the obvious assumption that more individuals and species would be found on a larger hull than a smaller one, all other factors being equal. What is well known, however, is that density of organisms is rarely evenly distributed across a vessel's hull, primarily due to recesses and general heterogeneity of hull areas as well as the effect of water currents. Certain locations have been identified as weak points in preventing biofouling settlement and development: drydocking support strips where antifouling paint could not be applied previously, waterlines, propellers, rudders, sea chests, intakes and their gratings, bilge keels and bow thrusters (Coutts, Moore & Hewitt, 2003; Coutts & Taylor, 2004). Internal fouling in ballast tanks is not thought to exist (Carlton, 1985).

Voyage routes/geographic location

The general routes and location of ports frequented by ships will have a major bearing on the composition and extent of biofouling assemblages. Large biogeographic spatial scales determine the species pool from which the assemblage will be comprised, and if different biogeographical provinces are visited, the species pool increases accordingly. At such large scales, general global diversity trends determine that vessels voyaging within the tropics would be considered more at risk to biofouling accumulation than those traveling within temperate or polar regions. At smaller spatial scales, the community composition of individual ports, anchorages and embayments will determine the fouling load. For more regional traffic, this can have implications for NIS loads of certain vessels (e.g. vessels traveling within the U. S. West Coast may be more prone to NIS if San Francisco Bay ports are frequented). The density of certain species is also expected to differ depending on whether a vessel has a regular route with frequent calls to certain ports (higher probability of species dominance) or travels to many different locations.

Vessel speed

Vessel speed plays a significant role in the density and survivorship of fouling assemblages. High speeds and their associated current velocities prevent fouling organisms from attaching to surfaces and can also remove or kill previously settled organisms. Settlement of organisms is often prevented at some current velocities (greater than 2 knots) because larvae are unable to attach (Doochin & Walton Smith, 1951). When speeds commonly exceed 20 knots, hull fouling (particularly on laminar areas) is not thought to occur while vessels are in transit (Minchin & Gollasch, 2003). In addition, certain taxa or morphologies (e.g. branching forms) are removed when exposed to high flow rates. Foster & Willan (1979) described how the slow voyage (\approx 6 kilometers [km] per hour) from Japan to New Zealand of a newly constructed oil platform resulted in extensive fouling with 12 barnacle species reported.

Voyage duration

Voyage duration is dependant on both distance traveled and the speed of the vessel. However, voyage duration acts independently of speed and distance as a factor regulating biofouling assemblages because the length of time at sea potentially impacts the survivorship. Physical variables and food availability can differ greatly between coastal and oceanic environments, and long spells in the open ocean may lead to the demise of many coastal taxa.

Harbor residence times

Since bio-adhesion and fouling accumulation are not thought to occur readily while vessels are en route from port to port, the residence times at dock or in port regions will determine fouling accumulation. Propagule pressure in some ports, where water residence times are increased because of restricted flow and high water retention, is thought to increase fouling pressure on hulls (Floerl & Inglis, 2003; Minchin & Gollasch, 2003). Trade patterns and particularly ship type influence docking times; bulkers average five days at port compared with just one day for car carriers (Merchants Exchange of Portland, 2005).

Physical factors

Temperature and salinity are the primary physical factors considered important in regulating hull fouling communities. Their effects are different depending on scale and organism tolerance. Over larger scales, trans-equatorial voyages (or other voyages between biomes) are thought to reduce survivorship of organisms by traveling through a range of conditions that are outside the physiological limits of the attached species. At smaller scales, regular passage through freshwater systems or calls to freshwater ports are known to purge hulls of most marine taxa (Brock, Bailey-Brock & Goody, 1999).

Season

Seasonality plays a role in determining hull fouling assemblages due to the reproductive periodicity of marine organisms and a general increase of propagule pressure (in temperate coastal zones) during Spring and Summer. The frequency of storms and harsh conditions also varies seasonally and can act as a major disturbance to hull fouling biota.

Drydocking periods and hull maintenance schedule

The period since the last drydocking can be the single most important factor determining fouling loads on ships; as the condition of antifouling measures on hulls deteriorates with time, biofouling accumulation increases. Current regulations adopted worldwide stipulate that the typical inter-drydocking period for commercial vessels be five years. The aforementioned drydocking strips may therefore have eluded re-treatment by antifouling paints for periods of up to ten years and beyond, thus presenting an opportunity for substantial colonization. In-water cleaning is also carried out on vessels in the interim periods between drydocks, and although many organisms are removed, the method is not as effective as drydocking and is considered, in smaller craft, to contribute to even greater biofouling accumulation afterwards (Floerl et al., 2005).

Antifouling paints and preventative measures

The advent of very effective antifouling paints is one of the reasons hull biofouling was considered less important as a vector of organisms than ballast water (Carlton, 1985). In the early 1970s, tributyltin (TBT) became the dominant antifouling paint applied to

vessels because it was hugely successful in preventing biofouling accumulation. Subsequently, its harmful effects on non-target organisms have prompted the IMO to enforce a complete prohibition by January 2008 on the use of organotin biocides (Nehring, 2001). The alternatives – among them, copper-based biocides in self-polishing copolymers and silicone-based paints that reduce adhesive abilities of organisms - are considered less effective than TBT, prompting a concern that hull-mediated translocations will increase in the near future (Nehring, 2001; Minchin & Gollasch, 2003). Fouling of vessel hulls is also influenced by the configuration of the cathodic protective system that individual vessels adopt. This can be a substantial area based on their placement and whether they have disintegrated, which can leave large areas unprotected.

Inoculation

Once an organism has survived the two initial periods of the transfer process (adhesion and translocation), successful recruitment to a new area depends on an inoculation mechanism or a way to jump ship. These mechanisms depend on either the individual organism acting as the inoculator itself or the organism releasing propagules that may become successfully established (Minchin & Gollasch 2003; Floerl et al., 2005).

- Gamete or larval release: this is considered the most frequent method of inoculating a new area. For gametes, the proximity and density of conspecifics (or an Allee effect) play significant roles in the likelihood of success. Cues to spawning, such as changes in temperature and salinity, and harbor water quality probably play significant roles as well. At least one instance of gamete release by a NIS followed by successful establishment of juveniles has been directly observed from a hull (in Hawaii – Apte, Holland, Godwin & Gardner, 2000).
- Individual organisms may colonize new areas simply by becoming detached from the hull. This may occur if vessels are rubbing against dockside fenders or tugs, but generally such contact occurs above the waterline. Although cases have been encountered for which no other explanation seems plausible (see Minchin & Gollasch, 2003), it is thought to be a rare occurrence because the nature of fouling

organisms is to remain attached to the substrate. Nehring (2001) has pointed out, however, that antifouling paints that reduce the adhesive abilities of organisms (as opposed to biocidal release) may inadvertently cause this type of detachment to increase as fouling organisms become more readily released.

- Mobile species may jump ship readily if they have managed to remain entrained in a hull recess or fouling matrix while the vessel was en route. This mechanism may previously have been more prevalent for two reasons; wooden hulls would have supported boring species and extensive fouling “many centimeters thick” (Carlton, 1985) would have allowed numerous mobile taxa to cling on for the journey. Dodgshun & Coutts (2002) and Coutts et al. (2003) have examined the threat of species transfer in ships’ sea chests and found numerous taxa capable of disembarking or producing a viable next generation (ovigerous female decapods).
- In-water cleaning: scouring or scraping the hull of a vessel underwater can result in species raining down on the benthos and surviving. To survive such a process, much depends on the ability of the individual organism to survive the physical disturbance and the suitability of the substratum onto which it falls (not necessarily directly below as currents may transport individuals away).
- Drydocks and ship yards remove fouling organisms from hulls and individuals may escape the dock floor to inoculate a new area. This mechanism is becoming more marginal because of codes of practice and regulations concerning the treatment of both biological and chemical wastes.
- Ship wrecks may act as a means for biofouling organisms to remain alive and intact after entering a new area (Minchin & Gollasch, 2003). Although this mechanism may peak periodically, such as at times of war, it is generally a rare event. Nonetheless, when it occurs it may require a swift response: a recently sunken trawler in New Zealand waters was successfully treated *in situ* to eradicate the threat posed by the invasive seaweed *Undaria pinnatifida* (Wotton, O’Brien, Stuart & Fergus, 2004).

1.5 The Lower Columbia River

With a drainage basin encompassing parts of Oregon, Washington, Idaho, Montana, Wyoming, Nevada, Utah, Alberta and British Columbia, the Columbia River is the largest river entering the northeast Pacific Ocean (Simenstad, Small, McIntire, Jay & Sherwood, 1990). Tidal influence extends 234 km upriver to the Bonneville Dam and 207 km upriver from the coast to Willamette Falls on the Willamette River (a major tributary to the LCR). It has the second largest runoff volume in the U. S. (≈ 244 billion m^3), creating ephemeral surface plumes that protrude into the coastal ocean and impact plankton and salmonid distributions (Morgan, DeRobertis & Zabel, 2005; De Robertis, Morgan, Schabetsberger, Zabel, Brodeur, Emmett, Knight, Krutzikowsky & Casillas, 2005). The estuary is typical of a salt wedge (low mixing) estuary with salinity intrusion stretching ≈ 50 km upstream from the mouth. Shipping to the Columbia River began with the earliest European American settlers in the early 1800s, but the area developed into a substantial port system after 1875 with the construction of a jetty at the mouth and dredging of the channel (Sytsma, Cordell, Chapman & Draheim, 2004). Today, five major ports are located on its lower reaches in Oregon and Washington, the largest of which is the Port of Portland (figure 1). The Columbia River port system is a major hub of agricultural exports in the U.S. and is the number one wheat exporter in the country.

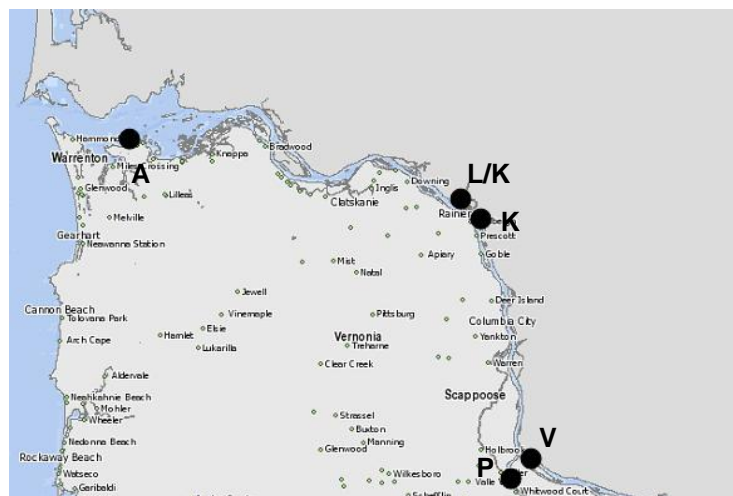


Figure 1. The location of the five major ports in the LCR. Astoria (A) is the furthest downriver port followed by the ports of Longview/Kelso (L/K) and Kalama (K). Furthest upriver are the ports of Vancouver (V) (Washington) and Portland (P) (Oregon). Map courtesy of Oregon Coastal Atlas (www.coastalatlant.net/index.asp).

The Lower Columbia River has 81 established NIS, and the rate of introductions has been increasing with time (Sytsma *et al.*, 2004). Although the majority of these NIS also occur in San Francisco Bay, the physical and hydrographical features of the LCR may have contributed to its distinctive assemblage of NIS (28 unique nonindigenous invertebrates) compared with other West Coast estuaries. Like other ecosystems, the environmental characteristics particular to the LCR contribute to its invasibility for certain organisms. For example, studies have shown that the salinity-intrusion trends and quick flushing rates of the LCR make it unlikely that mitten crabs, *Eriocheir* spp., will invade while the converse is true for Puget Sound (Hanson & Sytsma, 2005). On the other hand, temperature and salinity-intrusion patterns in the LCR are thought to have been significant for the establishment and abundance of the invasive copepod, *Pseudodiaptomus inopinus*, in the LCR and not in other Pacific Northwest estuaries (Cordell & Morrison, 1996).

The vectors of established NIS to the LCR are numerous and include shipping, aquaculture, ornamental escape, biocontrol, wildlife enhancement, and individual releases (Sytsma *et al.*, 2004). For invertebrates, the most dominant vector was shipping with 85 percent potentially associated with ballast water, solid ballast or hull fouling. Although 8 of the 35 invertebrate NIS may have been translocated via hulls, it was noted that this may be an underestimate because of insufficient data on hull-mediated transfers to the LCR and to other ports in general (Sytsma *et al.*, 2004). Two previous studies of hull fouling organisms have been conducted on two different vessels that transited the LCR. One was a replica 16th century sailing vessel that spent 35 days in the LCR and was subsequently sampled at various ports along an 800 km journey to San Francisco (Carlton & Hodder, 1995); the other was an examination of the fouling organisms attached to the hull of the USS MISSOURI after traveling to Hawaii from Puget Sound via a nine day stop in the LCR (Brock *et al.*, 1999). No study, including these two, has ever examined hull-mediated transfers of organisms to the LCR.

1.6 Aims

The purpose of this study was to conduct a preliminary examination of the extent and threat of hull-mediated transfers of organisms to the LCR. The analysis of this vector's

potential to translocate organisms to and (to a lesser extent) from the LCR focused on the ways in which density, magnitude and frequency of propagule pressure could cause an introduction with respect to vessels, organisms and the ecology of the LCR. Therefore, there were three main components of study: evaluation of wetted surface area (WSA) and shipping traffic; extent and composition of biofouling on vessel hulls; and fouling assemblages of the LCR estuary.

2. METHODS

2.1 Wetted surface area (WSA) and shipping traffic

For each vector of organism dispersal, the interaction of three components determines the success of an invasion or degree of invasion rate from that vector: density, magnitude and frequency. In general, the number of invasions to a location or from an invasion pathway increases as these three components increase. For ballast water, these terms are reflected in the numbers of organisms per volume of water, the amounts of water per de-ballast being released into the receiving waters, and the number of times de-ballasting occurs. For hull fouling, a similar analysis can be undertaken whereby the wetted surface area of a vessel is used to determine the space available for fouling species to occupy and be transferred; this is analogous to ballast water volumes for the BW vector.

WSA can be calculated as follows (from Van Maanen & Van Oossanen, 1988):

$$WSA = L (2T + B) C_M^{0.5} (0.4530 + 0.4425 C_B - 0.2862 C_M - 0.003467 B/T + 0.3696 C_{WP}) + 2.38 A_{BT} / C_B$$

where: L = length, T = draft, B = breadth, C_M = midship coefficient, C_B = blocking coefficient, C_{WP} = waterplane coefficient, A_{BT} = cross-sectional area of bulbous bow (calculated as a percentage of the immersed area of midship). The coefficients and bulb area percentages for different vessel types are published in Lewis (1988). Although length should technically be the waterline length of the hull, such data are not available for the commercial fleet so ship length is used.

WSA data can provide a measure of the potential for organisms to be transferred to the LCR via hull fouling. To estimate this potential for transfer, WSA data were calculated for ships arriving in the LCR. These data were derived from a combination of ballast

reporting databases kept by the Washington Department of Fish and Wildlife, the ABRPI (Aquatic Bioinvasion Research & Policy Institute) and the NBIC (National Ballast Water Information Clearinghouse) such that as accurate and complete a record of all arrivals to the LCR could be used. The database covered a period between July 2002 and June 2005. The completeness of the database compared favorably to similar analyses utilizing just one source (Minton et al., 2005; Verling, Ruiz, Smith, Galil, Miller & Murphy, 2005). Our database had just a 3.5 percent discrepancy between arrival totals compared with Maritime Administration (MARAD) data for 2003 and 2004. WSA data were then analyzed as a function of vessel type, time, origin, distance traveled (voyage duration), frequency of arrival and next port-of-call.

For the purposes of analyses, “foreign” arrivals and departures included those from outside the U.S. Pacific Coast exclusive economic zone (EEZ), with the exception of British Columbia and Alaska. “Coastal” vessels included those from the three U.S. Pacific Coast states, British Columbia and Alaska. The International Union for the Conservation of Nature (IUCN) classification of marine bioregions (figure 2) was also used. These bioregions form the basis of a classification of global marine coastal and oceanic zones based on environmental and biogeographical criteria. Although they have their limitations - *e.g.* boundaries between adjoining regions can be arbitrary for many taxa - they are useful in marine bioinvasion studies as a comparable framework for examining species ranges and shipping traffic as well as quantifying movement across broad, biologically meaningful marine systems. The “home” bioregion for the LCR encompasses the Pacific Northwest of the U. S. (figure 2).

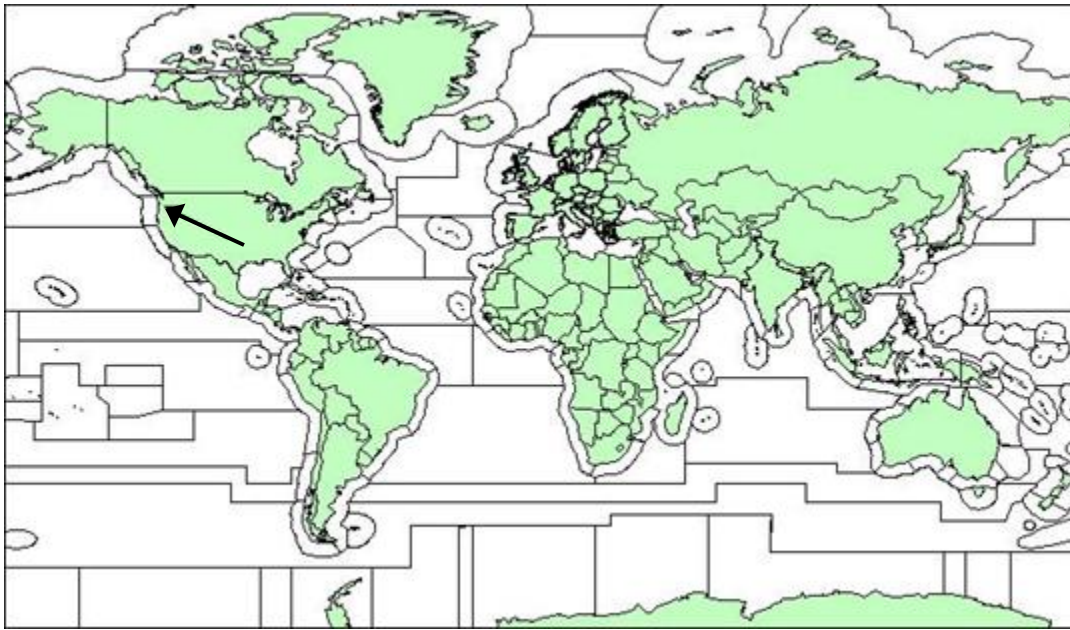


Figure 2. Worldwide Coastal Bioregions. Coastal bioregions of the world after a classification proposed by Kelleher, Bleakley & Wells (1995) of the International Union for the Conservation of Nature (IUCN). The arrow indicates the location of the LCR.

2.2 Extent and composition of biofouling on vessel hulls

The extent and composition of biofouling on vessel hulls was examined through sampling of drydocked vessels. Vessels were sampled on drydocks in Portland and were examined within hours of being taken out of water while hulls were still wet, most being sampled as soon as docking schedules allowed. The primary goals for each vessel sampled were to determine the biofouling percentage cover of the hull and to collect samples of all species comprising that biofouling. For each vessel, the extent of fouling over the entire hull was quantified (percentage cover) using photographs and notes. This was achieved primarily by noting the fouled proportion of different sections (divided into subsections if necessary) of each vessel. In addition, samples of all taxa encountered during a search of the accessible area were taken for identification purposes. Where possible (only for heavily fouled hulls), three randomly-placed quadrats (15 cm × 15 cm) were taken at the bow, midship and stern of each vessel on both port and starboard sides. A scraper was used to remove all taxa within the quadrat. Quadrat sampling was also carried out on heavily fouled propellers, rudders, drydocking support strips, sea chest gratings, bow thruster gratings, bilge keels, and water lines. For most vessels however, fouling loads

were not sufficient to warrant quantitative sampling. In addition, the following ship movement and maintenance data were collected from ship and dock operators where possible: last port-of-call, recent voyage history, time spent in the Columbia River prior to docking, last drydock or hull cleaning, and hull condition (antifouling paint status).

An additional analysis of hull inspection videos was also carried out to complement the assessment of biofouling on vessels that were inspected in the LCR. Of the 24 videos provided by maritime companies, only seven had sufficient coverage of the hull surface to be included in the analysis. There were two criteria for selection: a) the survey was a general one encompassing most of the hull from bow to stern and from the waterline to the keel and b) the length of the survey had to be a minimum of 30 minutes of recording time without focusing on one area for more than three minutes. Most surveys were discounted because they focused on propellers and rudders or a particular portion of the hull (failing criterion 'a'). Analysis of hull inspection videos focused on the biofouling percentage cover of the sampled area of vessel hull and broad taxonomic resolution of the biofouling composition. The video was paused when fouling organisms were encountered and an estimate made of percent cover within that frame.

2.3 The benthos of the Lower Columbia River

Analysis of invertebrate and fouling communities in the LCR was carried out using data from the Lower Columbia River Aquatic Non-indigenous Species Survey (LCRANS) and examination of settlement panels deployed in the LCR estuary. A multivariate examination of assemblage organization using non-metric multidimensional scaling (MDS in the PRIMER program, Clarke & Warwick, 2001) was carried out using LCRANS data based on presence/absence of taxa at different sites. Analysis of similarities (ANOSIM), a multivariate equivalent of Analysis of Variance (ANOVA), was used to test for differences between groups of samples in which the test statistic (r-value) ranges between zero (indistinguishable) and one (all within-group similarity is less than any between-group similarity).

Settlement panels were used to determine the colonization intensity (percent cover), species richness and species composition of fouling assemblages in the LCR estuary.

Preliminary assessments of dockside structures and rocks at the ports of Vancouver and Astoria revealed little other than ephemeral green algae. Studies have also shown that the salt water incursion into the estuary extends to approximately 50 km from the river mouth and the LCRANS survey suggested that the estuary be examined regularly for introduced species occurrences. Therefore, panels were deployed near the mouth of the Columbia only. Panels were submersed for 90 days (± 2 days) between April and August 2005 at six different sites (figure 3): on the south side, sites from the coast inward were south jetty (S1, S2), Hammond (S3, S4), Youngs Bay (S5, S6); on the north side, sites were at the north jetty (N1, N2), Chinook Point (N3, N4), Chinook Bay (N5, N6). Each panel array consisted of three PVC panels, measuring 15 cm \times 15 cm and lightly sanded, attached to two stainless steel bars. At each site panels were placed face down above the benthos at two locations (i.e. 6 panels per site and 36 in total). Upon removal, panels were photographed and returned to the lab for species identification (based primarily on Kozloff, 1996).

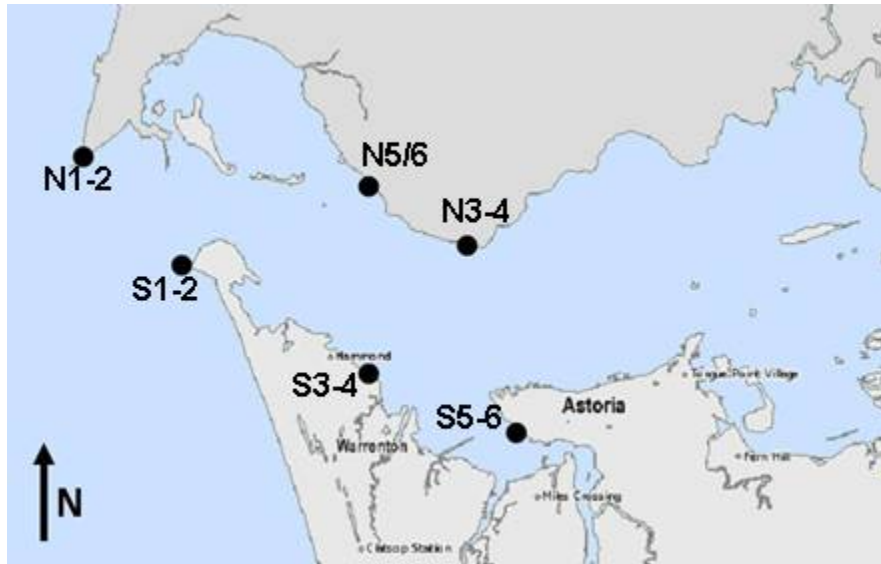


Figure 3. Locations of panels submersed for 90 days at the mouth of the Columbia River. The south and north jetty sites are nearest the coast, Youngs Bay and Chinook Point are the furthest upriver and Hammond and Chinook Bay are in between. Map courtesy of Oregon Coastal Atlas (www.coastalatlantis.net/index.asp).

3. RESULTS

3.1 Wetted surface area and vessel arrivals

In the three-year period analyzed, a total of 5801 arrivals were recorded in LCR ports. The destinations for 78 percent of these arrivals were the ports of Portland and Vancouver WA (most distant from the river mouth), with only 3.8 percent ending their voyage in Astoria (nearest to river mouth). The total WSA for the 36-month period was 40,547,351 m², with a monthly mean of 1,126,315 m² (standard deviation [SD] 90668 m²). Monthly fluctuations reached a maximum WSA of 1,336,613 m² and a minimum of 954,237 m², in November and February 2003, respectively (figure 4A). For all vessels, the pattern of monthly arrivals showed no seasonal trend with regard to shipping trade in the LCR, nor was an overall increase or decrease observed. Significant differences existed between total WSA arriving by vessel type ($\chi^2 = 52.54$, $p < 0.001$) with 58 percent of the total WSA contributed by bulk carriers, which accounted for the vast majority of arrivals (and some of the largest vessels) to LCR ports (figure 4B). There were significant differences in mean WSA between vessel types also (analysis of variance, $F = 1444.7$, $p < 0.001$); barges and miscellaneous vessels had smaller surface areas than the other four vessel types (figure 4C). There was less variability in WSA within barges and car carriers compared to the other vessel types. The largest WSA for a vessel arriving to the system was a tanker (27,067.87 m²) although in terms of the proportion of each vessel type, container ships had the largest area with 61 percent contributing a WSA of greater than 10000 m² (table 1).

Table 1. The percentage of arrivals for each vessel category in terms of WSA magnitude.

| WSA (m ²) | Barge (%) | Bulker (%) | Car Carrier (%) | Container (%) | Miscellaneous (%) | Tanker (%) |
|-----------------------|--------------|---------------|--------------------|------------------|----------------------|---------------|
| > 10,000 | 0 | 10.1 | 0.1 | 61.1 | 0 | 3.6 |
| 8 - 10,000 | 0 | 34.1 | 0.2 | 7.7 | 4.5 | 49.5 |
| 6 - 8,000 | 0 | 47.8 | 54.2 | 16.3 | 20.3 | 20.1 |
| < 6,000 | 100 | 8 | 45.5 | 14.6 | 75.2 | 26.8 |

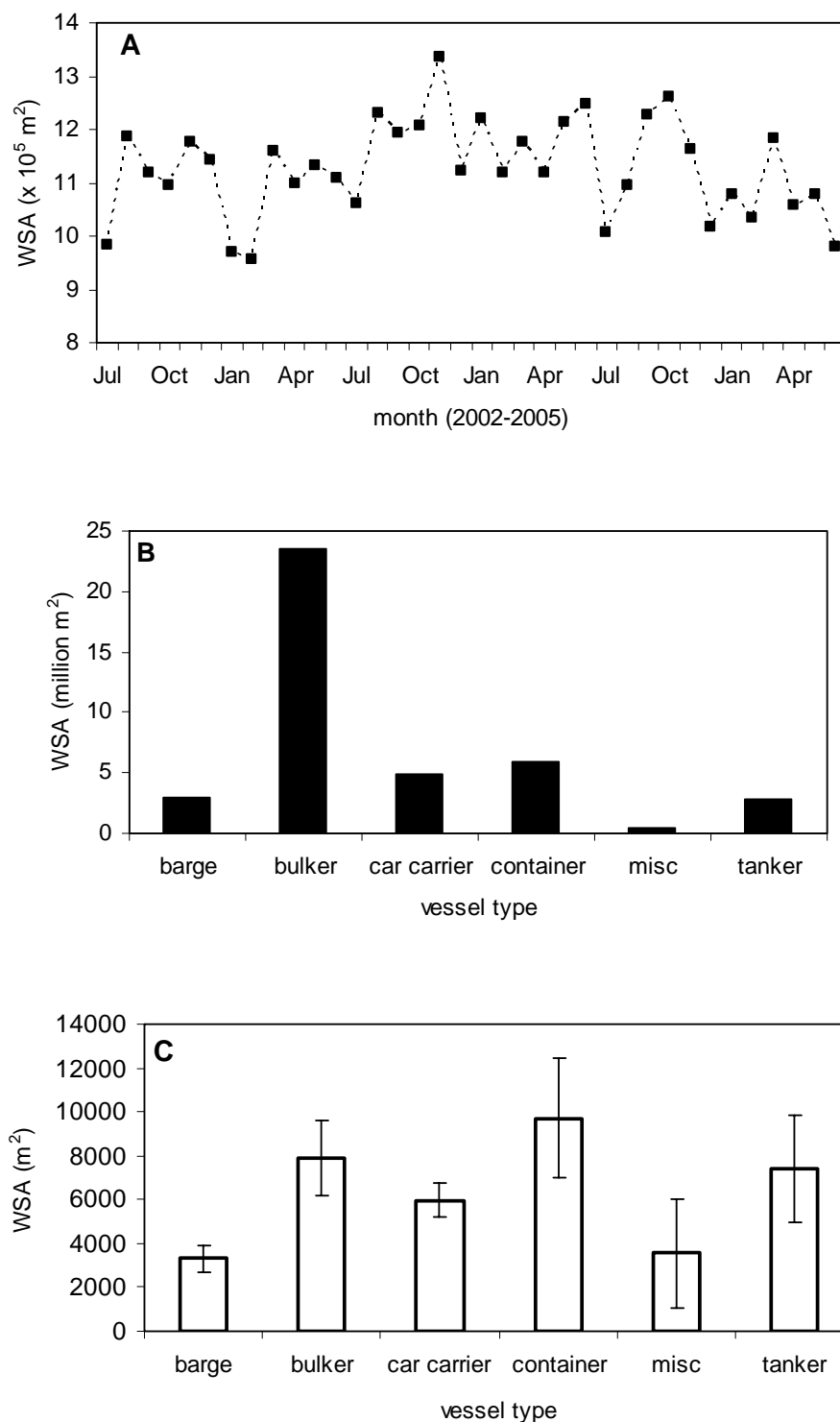


Figure 4. Monthly WSA arrivals and WSA contributions by vessel type between July 2002 and June 2005. The monthly WSA arrivals to the LCR between July 2002 and June 2005 (A), the cumulative contribution of each of six vessel types to total WSA arrivals (B) and the mean (and standard deviation) WSA per vessel arrival across vessel types (C). ‘Misc’ stands for miscellaneous vessels.

Vessels arriving to the LCR traversed the Pacific, Atlantic and Indian oceans - between latitudes of 42°S and 61°N - from 366 different ports throughout the world. They arrived from all heavily populated coasts of the three main oceans with the exception of the southeast Atlantic (figure 5). Sixty-six countries were represented, although 277 ports were located in just five; Japan (128), USA (57), China (36), Canada (31) and South Korea (25). A further 43 countries had only one last port-of-call for LCR arrivals. In terms of IUCN bioregions, LCR ports received vessels from 50 different bioregions amounting to 91 percent of the total WSA - *i.e.* only 9 percent of the total WSA arriving did not cross a bioregion boundary to get to the LCR. The last port-of-call for WSA arrivals was divided almost equally between foreign and coastal ports: 51 percent and 48 percent, respectively (1 percent unknown). With the exception of bulkers and containerships, the trend of WSA per vessel type was not mirrored by the number of bioregions from which vessels arrived (table 2). Miscellaneous vessels arrived from 12 bioregions - two more than car carriers and six more than barges - despite contributing the lowest WSA to the system. Car carriers contributed almost twice the WSA of tankers, but this surface area arrived from seven fewer bioregions. Barges were the most regional vessel type in terms of distance traveled to the LCR; 98 percent arrived from ports within or adjoining the home bioregion. In contrast, greater than 65 percent of bulkers and car carriers arrived from outside of the home or adjoining bioregions (Table 2).

Table 2. WSA arrival patterns according to bioregion. The number of IUCN bioregions from which vessels to the LCR arrived and the percentage WSA of each vessel category that arrived from within the 'home' bioregion, from adjoining bioregions, from within the Pacific (intra ocean), from outside of the Pacific (inter ocean) and from unknown sources.

| | barge | bulker | car carrier | container | miscellaneous | tanker |
|-------------------------------|--------------|---------------|--------------------|------------------|----------------------|---------------|
| • number of bioregions | 6 | 47 | 10 | 15 | 12 | 17 |
| • % within bioregion | 64 | 2.2 | 8.3 | 6.5 | 24.3 | 8.2 |
| • % from adjoining bioregions | 34.4 | 28.8 | 21.5 | 85.9 | 42.5 | 57.6 |
| • % intra ocean | 0.9 | 66.8 | 69.7 | 6.9 | 16.3 | 29.9 |
| • % inter ocean | 0 | 1.7 | 0.1 | 0.4 | 0.5 | 2.6 |
| • % unknown | 0.7 | 0.5 | 0.4 | 0.3 | 16.4 | 1.7 |



Figure 5. Previous ports-of-call for all vessel arrivals to the LCR between July 2002 and June 2005. There were a total of 366 different ports and in some cases the black dots on the map overlap. The divider between USA North and USA South is shown.

For all coastal arrivals (arrivals from the Pacific coast of North America), 9.6 million m^2 (49 percent) came from Canada and 18 percent arrived from within the ‘home’ bioregion (USA North in figure 6). For foreign arrivals, the Asian coast of the Northwest Pacific dominated last ports-of-call in terms of both number of ports and magnitude of WSA arriving. Just 16 percent of foreign WSA arrived from outside the Northwest Pacific (figure 6). Ships from Japan in particular dominated the magnitude of arrivals with ≈ 10.8 million m^2 - approximately 25 percent of all WSA arriving to the system over the three-year period. A further 4.3 million m^2 and 2.2 million m^2 WSA arrived from South Korea and China, respectively. By comparison, the WSA contributed by all other nations and bioregions was relatively minor, with the notable exception of Mexico, which was the only country outside of NW Pacific Asia from which greater than 1 million m^2 of WSA arrived.

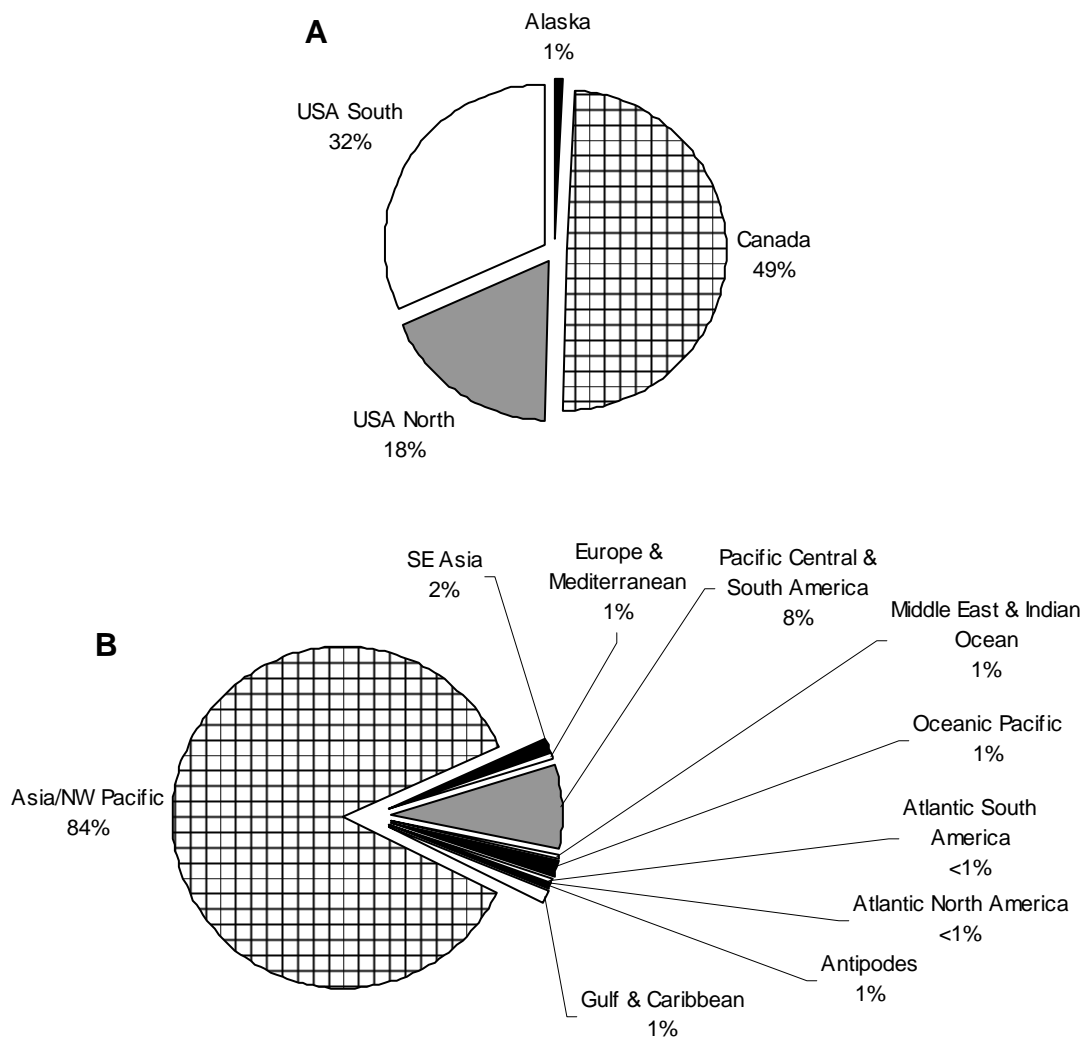


Figure 6. The percentage of WSA magnitude for coastal (A) and foreign (B) arrivals to the LCR. For coastal arrivals, the Pacific coast of the U.S. mainland was divided into south and north reflecting the division of this coastline into two bioregions in the IUCN classification scheme. For foreign arrivals, broader regions (incorporating numerous IUCN bioregions) were used to indicate the relative contribution of WSA from worldwide ports.

Analyses of the next port-of-call for departing LCR vessels was more ambiguous than previous port data because 16 percent of departures (in terms of WSA) had unknown destinations, primarily because of incomplete reporting or classified information. Nonetheless, the known next-port-of-call portion of departing vessels left the LCR for 273 different ports in 47 countries (figure 7). The most northerly port visited by a

departing vessel was the same as the northernmost previous port for incoming vessels – Anchorage, Alaska (61°N). The southernmost destination port for departures (Punta Arenas, Chile; 53°S) was further south than the previous port of incoming vessels (Bell Bay, Tasmania; 42°S), and it is notable that more southern hemisphere ports were listed for departures (40) than arrivals (17), despite fewer reports for the latter because of unknowns.



Figure 7. Next ports-of-call for all vessel departures from the LCR between July 2002 and June 2005. There were a total of 273 different ports and in some cases the black dots on the map overlap. Because many departing vessels did not report, 16% of voyage destinations from the LCR were unknown.

For known next ports-of-call, foreign ports comprised 49 percent of departing WSA and coastal ports the remainder (35 percent). Vessel WSA departing for coastal ports was divided evenly between Canada, USA north and USA south (≈ 33 percent each) with the remaining one percent departing for Alaska (figure 8A). The major difference between arriving and departing WSA for coastal ports was the net gain for the LCR from Canada (+ 5.5 million m^2) and the net loss in WSA from within its home bioregion (- 0.7 million m^2). As was the case with arrivals, WSA leaving for foreign ports was dominated by Asian ports of the NW Pacific with 75 percent of LCR departures (figure 8B). The next

most important region for departing WSA was SE Asia, particularly the Philippines, Indonesia and Thailand. Despite fewer ports, departing vessels traveled to more IUCN bioregions than incoming vessels traveled from: 52 compared to 50 but with 14.6 percent of known WSA destinations within the home bioregion.

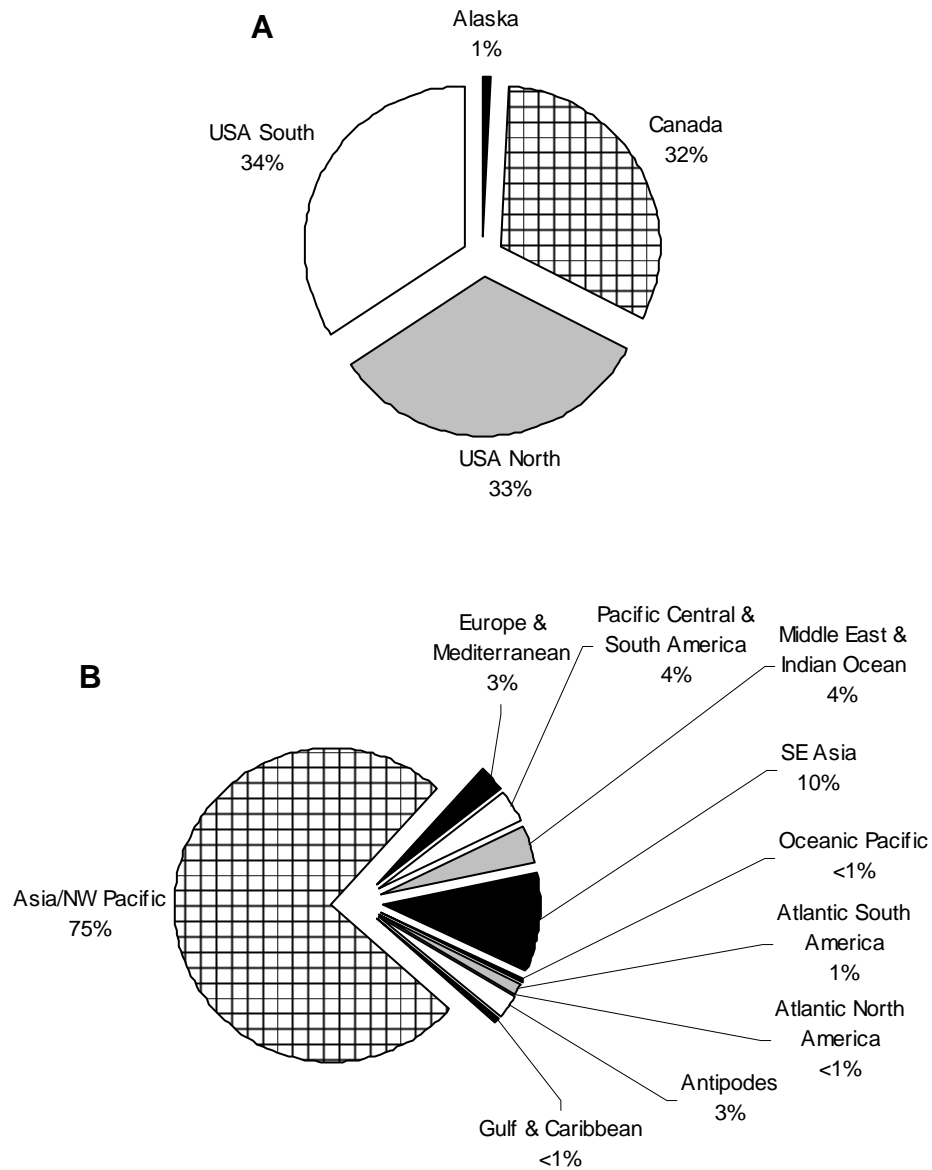


Figure 8. The percentage of WSA magnitude for coastal (A) and foreign (B) departures from the LCR. Regional designations are the same as figure 6.

In terms of bioinvasions ecology, each vessel type differed in terms of magnitude, frequency and behavior (operating conditions), warranting separate brief description.

Barges

Only barges arriving to the LCR following a sea voyage were included in this analysis. Incoming barges from upriver constitute a different prospect for bioinvasions research in this system. These barges are not required to report their entry to the LCR from the mid or upper stretches of the Columbia to any ballast reporting or maritime exchange body and so are not included in this analysis. The WSA of each individual barge was less than 6000 m² (table 1), making the size of individual vessels of this category the smallest of all six categories. For example, 44 percent more barges than containerships arrived, but barges contributed only half of the WSA of containerships. The volume of barge traffic over the course of 36 months meant that they were not the lowest contributor of WSA to the system (≈ 2.9 million m² in total); tankers and miscellaneous vessels contributed less.

Over the course of the analysis period, a steady increase in reported barge WSA was observed (figure 9). Barge WSA arrived overwhelmingly from coastal ports (greater than 98 percent) with 65 percent arriving from within Oregon and Washington. The destination for the majority of departing barge WSA was unknown because a mere 23 percent of barge vessels reported their next port of call. Of those that did report, none had foreign destinations and 36 percent of the coastal departures traveled outside of Oregon and Washington. As well as being almost entirely coastal in terms of incoming and outgoing WSA, a large number of individual barges visited the LCR on numerous occasions. One vessel visited on 63 different occasions, 17 percent of barges visited on more than thirty separate occasions and only 20 percent visited on one occasion only (figure 9).

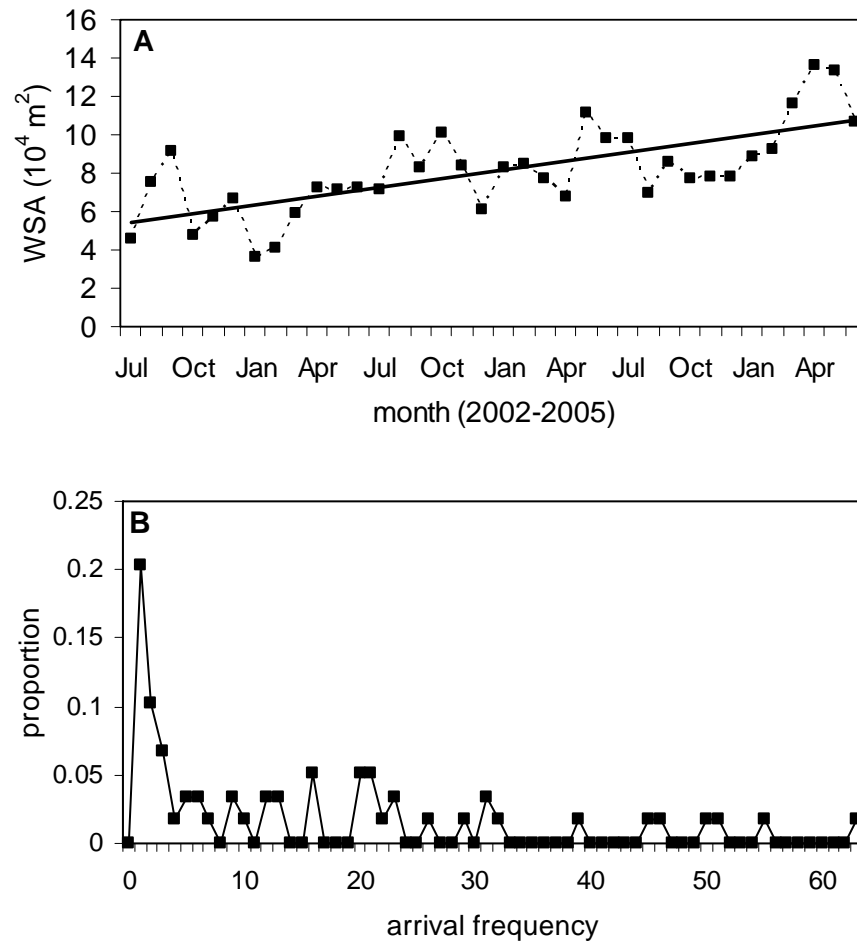


Figure 9. Barge Arrivals to the Lower Columbia River. Barge WSA arrivals to the LCR over the 36 month period from July 2002 to June 2005 (A) and the proportion of individual barge vessels in terms of frequency of arrival (B) to the LCR (n= 59).

Bulkers

Bulkers dominated patterns of WSA. They contributed greater than half of all vessel arrivals and comprised 44 percent of the vessels with a WSA greater than 10000 m². There was no seasonal trend, no general trend of increase or decrease and no major peaks or troughs over the three year period (monthly mean = 653500 m², standard error [SE] = 13212.8 m²). The proportion of bulkers visiting the LCR on multiple occasions was much lower than that of barges. A mere 2.7 percent of bulkers visited the system on more than ten occasions; about 57 percent (1704 vessels) visited just once (figure 10). The lack of port fidelity among this vessel type is also reflected in the source port of arrivals. Excluding the United States, bulkers arrived from 50 different countries and 47

different bioregions (country and bioregion borders do not overlap as some countries have many bioregions [*e.g.* Australia] and some bioregions incorporate numerous countries [*e.g.* the west coasts of six Central American countries are in one bioregion])). The majority of bulkier WSA arrived from foreign ports (68 percent), particularly from the NW Pacific ports in Japan, South Korea and China but also Taiwan, Eastern Russia and North Korea. A range of 9 – 15 days voyage duration would be expected for bulkers from this region. For departing vessels, a majority of bulkers traveled to foreign destinations (51 percent) but the data are more ambiguous, again because almost a quarter (23 percent) of all vessels did not report a next port-of-call. Despite the low rate of return visits by individual ships, a similar pattern to that of previous port was found for next port-of-call: Asian countries of the NW Pacific were the primary destinations for bulkier WSA departures.

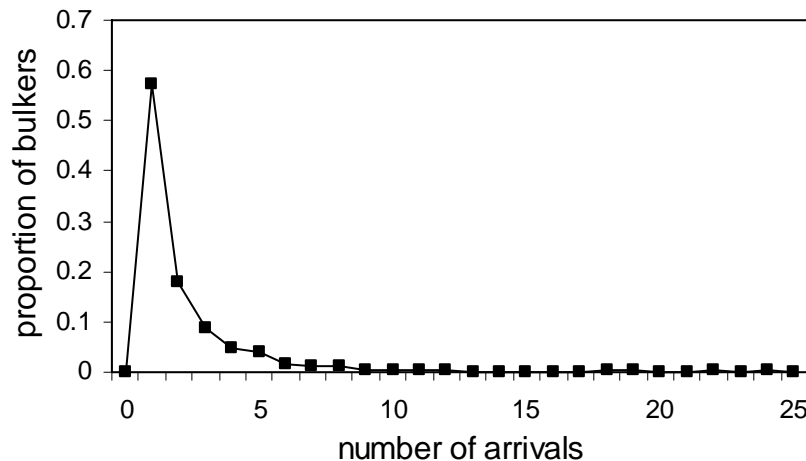


Figure 10. Histogram of bulkier vessel arrival frequency to the LCR (n=1264). Almost 60% were one-time arrivals.

Car carriers

Car carriers were relatively small vessels and more similar to barges and miscellaneous vessels in terms of proportions of WSA with less than 6000 m² per arrival than the other three vessel types (table 1). They had the largest proportion of vessels coming from foreign sources (70 percent), although the actual vessel numbers and WSA were far less than bulkers. Trends of arrivals and departures were similar in that relatively few countries were listed and within each of those countries, one port dominated (figure 11).

Car carriers arrived from 19 different foreign ports with certain ports being recorded often; for example, the Japanese ports of Toyohashi, Ulsan and Chiba were the previous ports for 272, 87 and 45 arrivals, respectively. Similarly for coastal arrivals, New Westminster (126) and Tacoma (67) were the most commonly visited previous ports indicating regularity of trade routes for this type of vessel. The next port of call was dominated by coastal ports; 54 percent traveled to coastal ports, particularly in California, whereas 20 percent voyaged to foreign destinations, and the remaining 26 percent (of WSA) did not report their next destination. The temporal trend revealed a fairly consistent pattern of arrivals with little variation from month to month (mean WSA 134743.61 m^2 , $\text{SE} = 3038.36 \text{ m}^2$) and return visits were relatively few. Greater than 40 percent of the 215 vessels were one-time visitors, and just one vessel visited on more than 20 occasions.

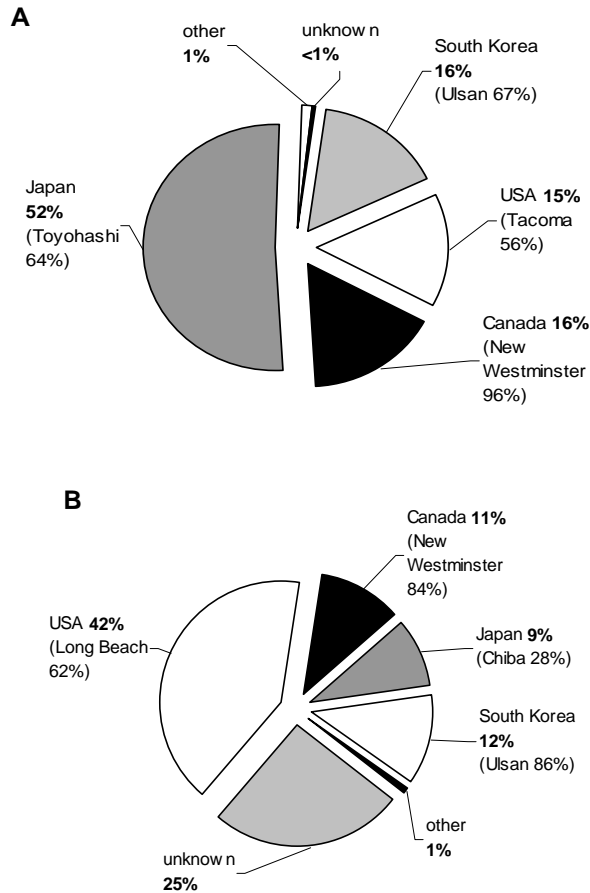


Figure 11. The percentage of car carrier WSA arriving from (A) and departing to (B) different countries. Values in bold represent the percentage per country of total car carrier WSA. Ports and values in parentheses represent the most dominant port in each country and the percentage of that country's total that arrived at or departed that port.

Containerships

Container ships were generally the largest vessel type with more than 61 percent of arrivals having a WSA greater than 10000 m² (table 1). Containerships were second to barges in terms of their proportion of incoming WSA from coastal voyages. Only 7 percent of WSA arrived from foreign sources, and of the 93 percent that arrived from coastal ports, 4.6 million m² (84 percent) came from British Columbia. Reporting of next ports of call only reached 72 percent, but 60 percent of this (47 percent of the total) traveled to foreign ports. The 612 arrivals were made by 112 different vessels and, although 37.5 percent visited only once, 22.3 percent visited more than ten times. A decline in containership WSA was recorded over the 3-year period, beginning after

August 2004, and coinciding with two containership lines removing Portland from their regular routes (figure 12).

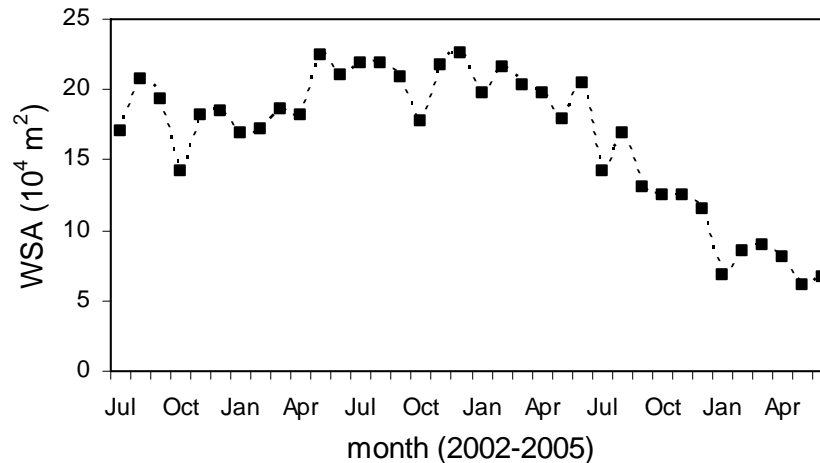


Figure 12. The temporal trend of WSA arrivals to the LCR from containerships in the three years analyzed. Note the decline of incoming WSA after the August 2004 pull-out of two container lines from the Port of Portland.

Miscellaneous vessels

By its nature, a category of miscellaneous ships is one that incorporates vessels that do not readily fit into other categories. This category included passenger ships, research vessels, naval vessels, cable ships, fishing vessels and other private craft large enough to warrant reporting of their arrival. Thus, the pattern of WSA arrivals was erratic over the 36 months analyzed and this was the only category to have a zero value for certain months (figure 13). A weak seasonal pattern was evident because of arrival peaks of passenger and naval vessels in summer, which coincided with festivals and other civic activities that attracted these vessels. In addition, these vessels contributed only about one percent of WSA within three years and each vessel was an infrequent visitor to the LCR. This category had the highest proportion of one-time visitors (65 percent). The WSA values for these vessels was generally low and some of the smallest vessels in the three-year database were in this category, including 22 vessels with less than 1000 m² submerged area. There was, however, a substantial proportion (25 percent) of vessels in this category with WSA values of greater than 6000 m². Coastal ports were the last and next ports-of-call for the majority of these vessels with 71 percent and 47 percent for arrivals and departures, respectively. A large proportion of vessels did not report their

prior (16 percent) and subsequent (47 percent) ports of call, primarily because of incomplete reports but also because the information for many of these vessels was classified. Ports in the Bahamas, Bermuda and the east coast of Canada were among the previous ports recorded for vessels unique to this category.

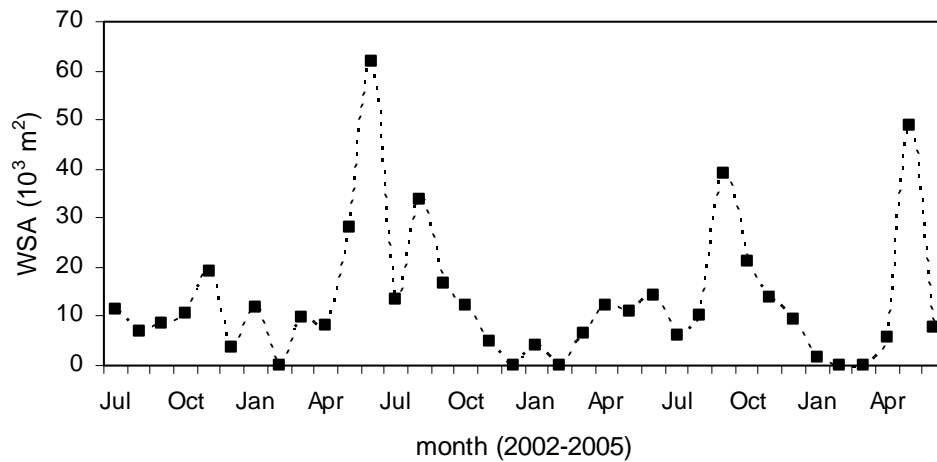


Figure 13. The temporal trend of WSA arrivals to the LCR from miscellaneous vessels between July 2002 and June 2005. Note that peaks and troughs generally coincide with summer and winter months, respectively.

Tankers

Tankers included all vessels designed to carry liquid cargo, including chemicals, liquefied natural gas and petroleum products. One such vessel traveled to the LCR 73 times – more than any other vessel - over three years, with all voyages beginning in Californian ports. Such port fidelity was not the norm for this category of vessels however; more than 80 percent of tankers and miscellaneous vessels were single or two-time visitors. A majority of vessels arriving from foreign sources were one time visitors (71 percent). Only three tankers returned to the LCR on more than ten occasions (figure 14). Sixty-five percent of previous, and 66 percent of subsequent, ports-of-call were coastal. Although far larger proportions of container ships and bulkers had WSA values of greater than 10000 m², tankers had the largest individual WSA values with four vessels exceeding 15000 m².

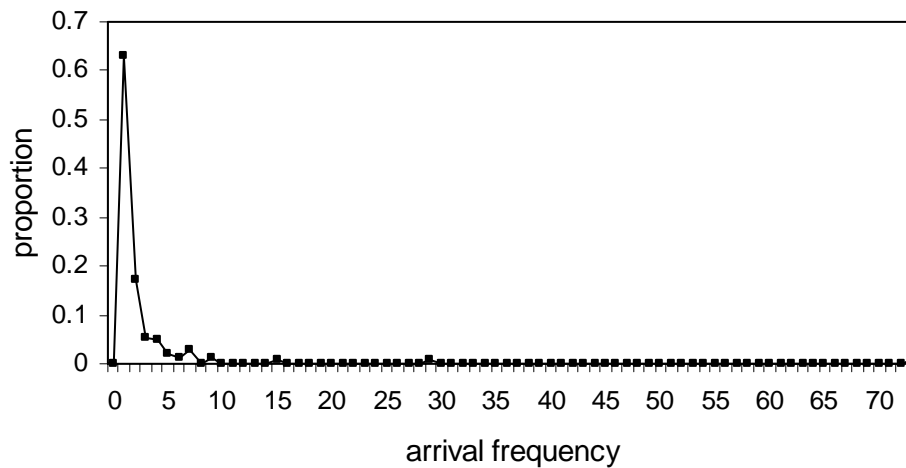


Figure 14. Histogram of tanker vessel arrival frequency to the LCR (n= 146).

3.2 Biofouling of vessel hulls

Vessels examined and hull surveys

Ten vessels were examined on drydock between August 2004 and August 2005 at one of the three floating drydocks in the LCR - Portland shipyard (2) and Sundial Marine drydock (Troutdale, OR). We examined and sampled four barges, one bulker, one tanker, and four miscellaneous ships (cutter, lightship, passenger ship, and dredge). The vessels surveyed varied greatly with respect to hull and voyage characteristics (table 3). Vessels varied with respect to size, ranging between approximate WSAs of 560 m² and 8673 m², but most (six) ranged between 1000 m² and just over 2000 m². With one exception, all previous drydockings to the present one occurred between 1.5 and 5 years ago. The vector potential for two vessels, *i.e.* the probability of bringing new organisms to the system, was zero because they were resident in the system; however their potential as an agent of secondary spread was not as equivocal. The four barges sampled in this study visited the LCR on a regular basis whereas the remaining four vessels were either first-time visitors or had called previously on just two occasions. Three vessels arrived from foreign ports, worked primarily in foreign waters and coincidentally were the three largest vessels (in terms of WSA) sampled in this study. The remainder worked only

coastal routes, mainly along Oregon and Washington. Only one vessel regularly traveled at speeds greater than 20 knots whereas most vessels' typical speed was less than 15 knots.

Table 3. Characteristics of the ten vessels examined on drydock. For each vessel, WSA (m²), age (years), most recent inter-drydock duration, status as a caller to LCR ports, port or region from which it arrived, typical port duration, typical speed and other notes are reported. Data were provided by vessel operators or drydock personnel.

| Vessel Type (ID) | WSA (m ²) | Age (yr) | Last drydock | LCR visits | Last port / region | Typical port duration | Typical speed | Notes |
|------------------|-----------------------|----------|--------------|--------------|----------------------|-----------------------|---------------|-----------------------------------------------------------------|
| Barge #1 | 1946.9 | <20 | <2 years | frequent | Alaska | 2-3 days | <15 knots | In LCR ≈1 month prior to docking |
| Barge #2 | 1039.5 | 41 | > 4 years | frequent | Washington | 2-3 days | <15 knots | In LCR 3 months prior to docking |
| Barge #3 | 1648.8 | 39 | > 4 years | frequent | Coos Bay | 1-2 days | <15 knots | Runs between Coos Bay, Aberdeen and LCR |
| Barge #4 | 1658.3 | 28 | ≈3.5 years | frequent | Washington | 2-3 days | <15 knots | Runs between OR and WA ports |
| Bulker | 8227.5 | 14 | ≈2 years | 2 since 2002 | Onsan, South Korea | 2-3 days | 18-20 knots | Unplanned docking because of navigation difficulties |
| Cutter | 2016.0 | 34 | ≈4 years | none | Hawaii | days to weeks | 28 knots | 6 days in LCR prior to docking, based in Hawaii, recently in AK |
| Dredge | 1074.2 | 23 | ≈1 year | 2 since 2002 | Coos Bay | days to weeks | 18 knots | Works the coast of CA, OR and WA |
| Light ship | 559.6 | 54 | 16 years | resident | Astoria / Portland | months | n/a | LCR resident and usually dock side |
| Passenger | 652.9 | 17 | 5 years | resident | Portland / LCR | 1 day - variable | <12 knots | LCR resident, tours of the LCR/Willamette |
| Tanker | 8673.4 | 14 | >3 years | none | Classified / foreign | unknown | 20 knots | Replenishing vessel, mainly coastal |

Taxon richness and abundance

Representatives of eight broad taxonomic groups were found on the hulls of the ten vessels examined (table 4). No vessel was found to be devoid of biota. An average of three broad taxa (SD = 2) were found per vessel, with a range from one to seven. Each major taxon occurred on an average of 3.75 vessels (SD = 2.8). Green algae were present on all but one vessel and barnacles were found on seven. The remaining taxonomic

groups were found on four or fewer vessels each, with sponges found on just one ship. Amphipods, although not a sessile fouling organism, were included on this list because when present, they were found in high numbers and they are associated with fouling communities.

Table 4. The occurrence of broad taxonomic groups on each of the ten vessels examined. The total number of taxa per vessel and the total number of occurrences on vessels of each taxon are also shown.

| Taxonomic Group | Barge #1 | Barge #2 | Barge #3 | Barge #4 | Bulker | Cutter | Dredge | Light-ship | Pass-enger | Tanker | Total |
|-----------------|----------|----------|----------|----------|----------|----------|----------|------------|------------|----------|-------|
| Chlorophyta | - | X | X | X | X | X | X | X | X | X | 9 |
| Barnacles | X | - | - | X | X | X | X | X | - | X | 7 |
| Bivalves | - | - | - | - | - | X | - | - | - | X | 2 |
| Bryozoans | - | - | - | - | - | X | - | X | - | X | 3 |
| Hydroids | X | - | - | - | X | - | - | X | - | X | 4 |
| Sponges | - | - | - | - | - | - | - | - | - | X | 1 |
| Tube worms | - | - | - | - | - | X | - | - | - | X | 2 |
| Amphipods | - | X | - | - | - | - | - | X | - | - | 2 |
| Total | 2 | 2 | 1 | 2 | 3 | 5 | 2 | 5 | 1 | 7 | |

Among all vessels, 32 distinct organisms (species) were recorded. Bryozoans were the most species-rich group with 11 unique taxa, followed by barnacles (5). Only three vessels had more than four species – one resident LCR vessel (lightship) and two that traveled from foreign sources prior to docking (figure 15A). These three vessels were also the only ones with fouling communities covering more than 60 percent of their hulls (figure 15B). The other vessel that traveled from a foreign source had three distinct taxa attached. The tanker had the highest number of higher taxa and distinct organisms with 14 unique taxa belonging to seven broader taxonomic groups (figure 15A). In general, those vessels that had a high percentage of their hulls covered in biofouling also had a high number of species. One exception is the passenger vessel that had a substantial percentage (55 percent) of its hull covered by just one green algal taxon. The four barges that travel frequently between the LCR and coastal waters had low percentage cover of biofouling.

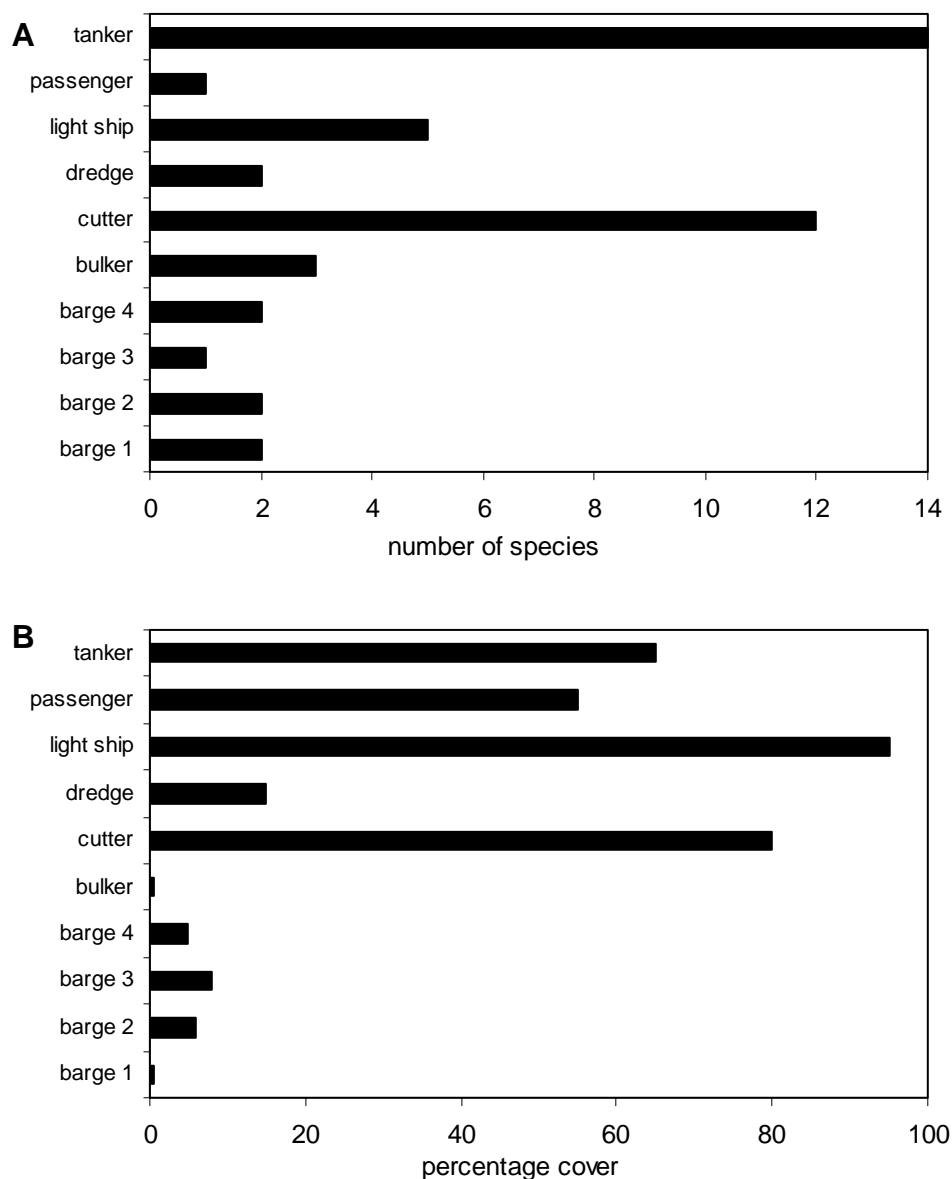


Figure 15. The number of unique taxa [species] (A) and the percentage cover (B) of fouling biota on the hulls of ten vessels examined on drydock in the LCR.

Density and distribution of taxa on hulls

The density of biofouling and distinct taxa varied widely within and between vessels. Within vessels, biofouling was distributed unevenly across the hull; three lightly fouled vessels had no biota attached to the hull surface below the waterline (table 5). For four heavily fouled vessels (those with greater than 40 percent cover – figure 15B), all areas of the underwater surface supported biota and the hulls were covered to such an extent that organisms were found both within and outside of drydocking support strips.

Furthermore, the cutter showed a distinct pattern of banded heavy and light fouling based on the position of previous drydocking support strips, but the other three vessels were covered sufficiently for the location of previous support strips to be obscured (figure 16). The bulker had a very distinctive pattern of fouling distribution on the hull; only clumps of a hydroid species occurred within drydocking support strips. The waterline of all but one vessel had biota, primarily green algae, and the biofouling of two of the barges was restricted to the waterline only. Rudders and propellers were similar in terms of fouling extent and composition. Neither appendage was fouled on the dredge whereas both were lightly fouled on the passenger vessel and both were heavily fouled on the tanker. Only half of all vessels' intakes/gratings were fouled with biota.

Table 5. Occurrence of biota by vessel location. A single X denotes presence of biofouling and a double X indicates heavy fouling. Dashes indicate absence of biota. Grey cells signify the absence of that hull location on the vessel during the survey.

| | Hull | Waterline | Rudder | Propeller | Intakes / gratings |
|-----------|------|-----------|--------|-----------|--------------------|
| Barge #1 | X | - | | | X |
| Barge #2 | - | XX | | | - |
| Barge #3 | - | XX | | | - |
| Barge #4 | X | X | | | - |
| Bulker | X | X | | - | - |
| Cutter | XX | X | XX | XX | X |
| Dredge | - | X | - | - | - |
| Lightship | XX | X | XX | XX | X |
| Passenger | XX | X | X | X | X |
| Tanker | XX | X | XX | XX | XX |



Figure 16. Contrasting fouling patterns on the hulls of two vessels. The tanker (left) has heavy fouling distributed patchily around the curved and flat-bottom area of the hull with no clear evidence of previous drydocking support strips. Examples of areas with little or no fouling are circled. The Cutter (right) has clear banding along the keel with heavy fouling where previous support blocks prevented application of antifouling paints and light fouling in-between with clear boundaries (indicated by the arrows) between patches.

The organisms on vessels without extensive biofouling on portions of their underwater surfaces and with low species richness were all directly attached to the hull. The heavily fouled lightship, cutter, and tanker all had fouling organisms attached to primary and secondary substrata (*i.e.*: attachment directly to the hull and to other organisms [table 6]). On the lightship, the barnacle, *Balanus improvisus*, occurred at a density averaging 22.4 (SD = 10.2) organisms per sample, and within each 15 cm × 15 cm quadrat (n = 21), 31 (SD 15) *Americorophium* spp (amphipods) were counted within the fouling matrix. These two species plus the unidentified hydroid were found in every sample, and all three occurred directly on the hull and on each other. The bryozoan, *Fredericella indica*, was found in just one quadrat but was only found adhering directly to the hull and not to other taxa. For the cutter and tanker, taxa that were found infrequently in samples tended to be attached only to other organisms and not directly to the hull (table 6). On the cutter, spirorbid and serpulid (including species of Hydroides) polychaetes were found on the keel at mean densities of 137.2 (SD = 25) and 29.8 (SD = 8.7) organisms, respectively, per sample (n = 9) and were both primary and secondary foulers. Five species that occurred in just a third or fewer samples on this vessel were not found attached directly to the hull. Likewise, six species that were encountered infrequently on the tanker were secondary foulers only; the eight others were found in most samples adhering directly to the hull with most (6) also found attached to other species. Thus the general pattern for these three vessels was that taxa that occurred in high densities were primary and secondary foulers whereas those that were rare were found only on secondary sources of attachment (with one exception).

Table 6. Organisms present on the hulls of ten vessels examined on drydock. The breakdown of distinct taxa found on each ship is provided. Also noted is whether the taxon occurred on the hull of a vessel (primary [P]) or attached to other organisms (secondary [S]) or both (P/S).

| Vessel | Broad Taxon | Lowest Taxon | Primary (P)/Secondary(S) |
|------------------|-------------|--------------------------------|--------------------------|
| Barge #1 | Cirripedia | <i>Balanus</i> sp | P |
| | Hydrozoa | <i>Obelia</i> sp | P |
| Barge #2 | Chlorophyta | Cladophora sp | P |
| | Amphipoda | <i>Americorophium</i> spp | P/S |
| Barge #3 | Chlorophyta | <i>Enteromorpha</i> sp | P |
| Barge #4 | Chlorophyta | <i>Enteromorpha</i> sp | P |
| | Cirripedia | <i>Balanus</i> sp | P |
| Bulker | Chlorophyta | Chlorophyta spp | P |
| | Cirrepedia | Balanidae sp | P |
| | Hydrozoa | Unidentified Hydroid A | P |
| Cutter | Chlorophyta | Chlorophyta spp | P |
| | Cirrepedia | <i>Balanus amphitrite</i> | P/S |
| | Bivalvia | Ostreidae sp A | P/S |
| | | <i>Ischadium</i> sp? | S |
| | Bryozoa | <i>Watersipora subtorquata</i> | P/S |
| | | <i>Bugula</i> sp | S |
| | | <i>Schizoporella</i> sp A | P/S |
| | | <i>Hippoporidridae</i> sp | P/S |
| | | <i>Buffonellodidae</i> sp | S |
| | | Unidentified Bryozoan | S |
| | Annelida | Spirorbid sp | P/S |
| Dredge | | Hydroides sp | P/S |
| | Chlorophyta | Chlorophyta spp | P |
| | Cirrepedia | <i>Balanus</i> sp | P |
| Lightship | Chlorophyta | Chlorophyta spp | P |
| | Cirrepedia | <i>Balanus improvisus</i> | P/S |
| | Hydrozoa | Unidentified hydroid B | P/S |
| | Bryozoa | <i>Fredericella indica</i> | P |
| | Amphipoda | <i>Americorophium</i> spp | P/S |
| Passenger | Chlorophyta | Chlorophyta spp | P |
| Tanker | Chlorophyta | Chlorophyta spp | P |
| | Cirrepedia | <i>Megabalanus</i> sp | P |
| | Bivalvia | Ostreidae sp B | P/S |
| | | <i>Mytilus</i> sp A | S |
| | Bryozoa | <i>Watersipora subtorquata</i> | P/S |
| | | <i>Schizoporella</i> sp B | P/S |
| | | <i>Tubilipora</i> sp | S |
| | | <i>Stylopoma</i> sp? | S |
| | | <i>Candidae</i> sp | S |
| | Hydrozoa | Unidentified Hydroid C | S |
| | Annelida | Spirorbid sp | P/S |
| | | Serpulidae sp (keeled) | P/S |
| | | <i>Hydroides</i> sp | P/S |
| | Porifera | Unidentified sponge | S |

Analysis of vessel hulls using video footage

Fouling of the seven vessels examined using video footage showed that most had very few taxa covering very small proportions of their hulls. Only two vessels had biofouling on more than three percent of the sampled area (table 7); Bulker B had extensive algal covering of its waterline forming a band around the ship that was ≈ 3 m deep. Tanker B was heavily fouled after a prolonged period of inactivity within the LCR. For the other vessels, the dominant taxa were barnacles and tube worms that occurred in isolated patches, generally in areas of hull with scratches in the paint or metal on propellers and drydocking support strips. Although all except one of these vessels traveled to the LCR from Asia, a lack of recent operational data and hull maintenance information precluded any broad conclusions regarding fouling levels. One major factor may have been the time spent in the LCR prior to the video surveys, but that information was unavailable.

Table 7. Characteristics and details of biofouling of seven vessels examined using underwater hull survey video footage. For each vessel, WSA (m^2), video length (minutes), country of last port, countries of last port on previous visits to the LCR, percent cover of fouling biota, primary locations where fouling occurred and taxa found are provided.

| Vessel Type (ID) | WSA (m^2) | Video length | Country Last Port | Previous port countries before prior LCR visits | % Cover | Main Area | Taxa |
|-------------------------|--------------------------------------|---------------------|--------------------------|-----------------------------------------------------------|----------------|------------------------------------------|-----------------------------------|
| Bulker A | 11451 | 60 | China | Mexico (1), China (1) | <1% | none | tube worms |
| Bulker B | 7400 | 32 | Japan | Japan (15) | 10% | waterline, bulbous bow | chlorophyta |
| Bulker C | 8504 | 48 | Japan | Japan (4), Mexico (1) | <1% | none | barnacles |
| Bulker D | 9304 | 121 | Japan | Japan (4), California (1) | <1% | none | tube worms |
| Bulker E | 1233 | 69 | South Korea | Japan (2), South Korea (2), California (1) | 3% | dry dock support strips | tube worms |
| Tanker A | 16114 | 31 | Philippines | Singapore (6), California (5), Bangladesh (1), Hawaii (1) | 2% | propeller | barnacles, tube worms |
| Tanker B* | 8386 | 88 | Alaska | California (1), Washington (1) | 85% | hull, intake gratings, propeller, rudder | chlorophyta, sponge-like material |

*Tanker B was laid up in the LCR for >12 months prior to video survey.

3.3 Benthic taxa of the LCR

LCRANS data

During the LCRANS survey, 324 species (or distinct taxa) were collected at 134 different sites in the LCR. Invertebrates (benthic and planktonic) accounted for 63 percent of all species, and the fouling community included representatives of five phyla: porifera,

cnidaria, arthropoda, bryozoa, and mollusca. Despite the data being collected over a length of more than 200 miles on the river, there were no clear trends in species richness with respect to distance upriver. MDS plots also revealed that there was little differentiation of assemblages of benthic and planktonic fauna (ANOSIM global-R for both plots < 0.26; figure 17). For benthic fauna, despite the overall similarity between groups, sites in the estuary tended to cluster more together than with upriver sites (most estuary sites are on the left hand side of figure 17A).

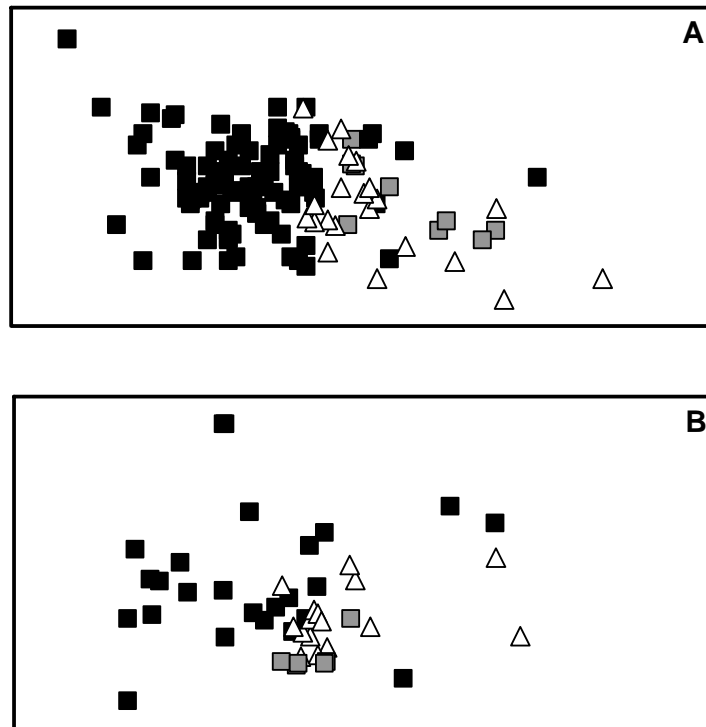


Figure 17. MDS plots of (A) benthic and (B) planktonic fauna in the LCR based on presence/absence data from the LCRANS survey (Sytsma et al., 2004). For both plots, black squares = less than 50 miles upriver, grey squares = 50 – 100 miles upriver and open triangles = > 100 miles upriver. The stress values for A and B are 0.14 and 0.08, respectively. Note the division between the majority of estuary sites (left side of the plot) from upriver sites (right) for benthic taxa (A).

Fouling panels

Only five distinct organisms were found on the 30 replicate panels that were submerged for 90 days each in the LCR estuary. The panels from one site (North Jetty, N1 and N2) could not be retrieved due to construction work on the jetty. The species found were *Mytilus* sp (mussel), juvenile *Balanus* sp (barnacle), *Cordylophora lacustris* (hydroid),

Hydra sp, and *Enteromorpha* sp (green alga). With such low numbers, there was no significant difference in species richness between sites, but there was much greater variability in terms of percentage cover (figure 18). The panels located in marinas (S5, S6, N5 and N6) had significantly greater percent cover of organisms than all other sites. *Cordylophora lacustris* dominated panels in Youngs Bay (S5 and S6; figure 19) on the south side of the estuary while the Hydra sp was the dominant fouler in Chinook Bay (N5 and N6). Despite the high levels of fouling on the south jetty intertidal rocks, dominated by *Balanus glandula* and *Mytilus* spp, very little settlement was observed on the panels.

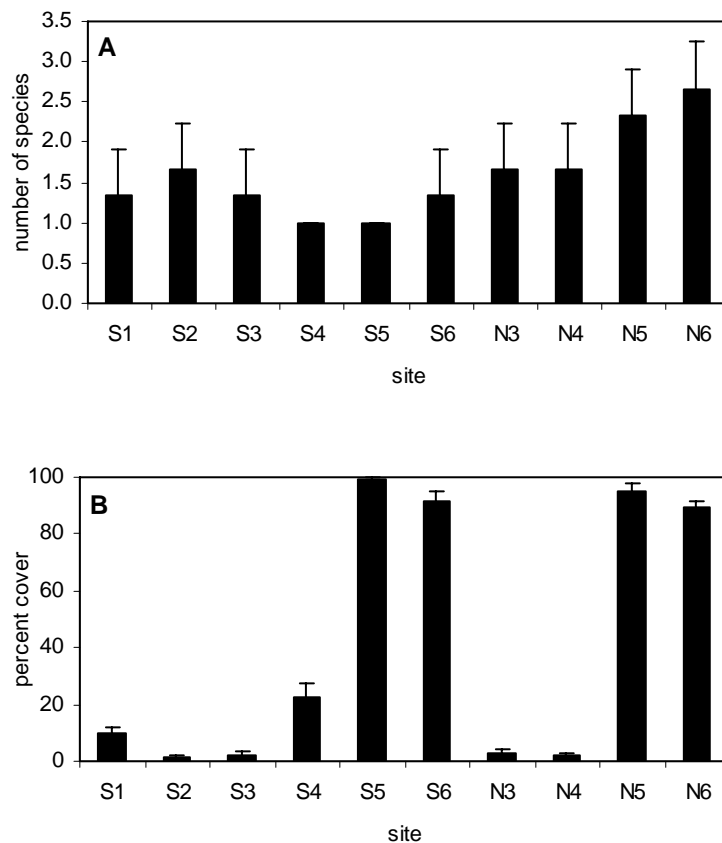


Figure 18. The number of species (A) and the percentage cover (B) on settlement panels deployed at 5 locations (2 sites per location) in the LCR. Error bars represent the standard deviation of three replicates per site.



Figure 19. Contrasting fouling levels on settlement panels. The panel on the left was submerged on the south jetty (S1) and has little fouling. The panel on the right (S5) is smothered by the hydroid *Cordylophora lacustris*.

4. DISCUSSION

The exact empirical probability that a NIS could arrive to the LCR on one or more vessel hulls and become established is unknown and probably unknowable. This is because at an absolute level, it would be impossible to determine the exact number and identity of all species that could attach to hulls, survive a voyage, and inoculate any new area.

However, quantifying the variability among factors that determine propagule supply and the likelihood of establishment may provide a sound basis for determining the relative risk between areas, from certain taxa, or from specific vectors. The foundation of such a risk analysis stems from two important characteristics of introductions: 1) a positive causal relationship exists between the supply of propagules and the probability of establishing a nonindigenous population (Grevstad, 1999; Lonsdale, 1999; Ruiz et al., 2000; Minton et al., 2005); 2) establishment depends on propagule quality (e.g. fitness of potential founder individuals) and environmental tolerance as well as openness of the recipient site in terms of habitat availability, competition and predation (Lonsdale, 1999; Verling et al., 2005).

Inoculation of a recipient region by any vector is a function of density, magnitude, frequency and duration of propagule supply. For hull fouling, this equates to the number of organisms per unit area (or percentage cover) attached to the hull, the size of the underwater surface area, the regularity with which these same organisms are transported to the region and the length of time over which the inoculation occurs. For other vectors

the definitions differ, including ballast water for which density and magnitude are measured using concentration of organisms and discharge volumes, respectively. This highlights one key difference between the two shipping sub-vectors; the organisms transported in ballast water are often withheld from the environment but the propagules supplied by hull fouling always represent a potential new delivery of NIS. This has repercussions based on trade patterns because certain ports act as net importers or exporters of ballast water as a result of certain vessel types (such as bulkers and oil tankers) having uneven bidirectional ballasting patterns (Smith et al., 1999). Therefore, all arrivals are not equal for ballast water, but they are possibly more even in terms of propagule supply for hull fouling. Furthermore, hulls support an assemblage of organisms where each port's biota potentially act as a possible contributor of propagules; last port-of-call is not such a faithful indicator of the possible source of ballast water organisms to a recipient port (Noble, Sytsma, Ruiz & Simkanin, in prep).

4.1 Potential magnitude and frequency of propagule supply

In the LCR, the potential magnitude of propagule supply is substantial due to a WSA of approximately 1.12 million m² per month arriving to the five major ports. The average annual figure of 13.5 million m² equates to around 5 percent of the U.S. total (based on an estimate by Ruiz et al., in prep) or more than 2500 football fields of surface area. This potential colonizable surface area for fouling biota varied by ship type which in turn varied by donor region and frequency of arrival. Bulkers and miscellaneous vessels occupied opposite ends of the spectrum in terms of WSA arrival. Bulkers contributed over half of the total whereas miscellaneous vessels had just a one percent share. However, each vessel type had WSA delivery characteristics that may have a negative influence in terms of nonindigenous propagule supply to the LCR. For example, miscellaneous vessels may have been minority contributors of WSA but when these underwater surfaces and their associated biota did arrive, it generally occurred in summer months. Barges contributed just seven percent of the total WSA (low magnitude) but many of these vessels were repeat visitors to the LCR (high frequency,) and it appears from ballast reporting data that barge traffic is increasing. Despite a decline in the number of arrivals because of container lines no longer trading in the Port of Portland,

containerships had the largest mean WSA per vessel. Car carriers not only tended to arrive from the same region, but much of the surface area arrived from the same ports (and probably the same terminals within these ports). Individual tanker vessels were both the largest and most frequent callers to the LCR. Many of these characteristics may function to increase the inoculation potential of each vessel type to the LCR.

Average vessel size and total WSA contributed per vessel type provide readily interpretable comparisons of inoculation risk. For each vessel type, the average vessel surface and total WSA contributed differed significantly in terms of their potential propagule delivery to the LCR. Beyond these measures, the threat of inoculation within and between each vessel type is difficult to gauge. For example, the proportion of vessels repeatedly returning to the same port may be an indicator of high frequency of (the same) propagule supply which increases the probability of establishment. Thus, barges carry the greatest risk to the LCR in this respect while car carriers and tankers pose a lesser risk. However, although tankers as a vessel type had a low proportion of returning vessels, one vessel came to the LCR almost twice per month from the same California ports. Without any knowledge of its fouling load, this frequency of propagule supply from the same region theoretically poses a high risk of establishment; the return of propagules from the same populations every other week may counteract any problematic density or proximity issue that a population of individuals on this vessel might have. Consequently, there is a comparatively minimal risk of inoculation frequency across all tankers but one of these vessels posed the greatest individual risk.

Other vessel characteristics, not examined explicitly here, may also operate to heighten propagule pressure to the LCR within certain vessel types. The Merchants Exchange of Portland (2005) reported that the average stay in port (different from overall time spent in the LCR) for bulkers was five days, car carriers one day and barges, containerships and tankers two days each. If such port durations are typical for all ports, then bulkers clearly have a greater potential for hull colonization than other vessels – a potentially crucial factor to a port system that is dominated by this vessel type. Often described as the ‘workhorses’ of the sea, it may also be true that hull maintenance of bulkers is less rigorous than other vessel types and they generally travel at slower speeds than

containerships, car carriers and tankers. In their analyses, Verling et al. (2005) compared vessel arrivals over three years to 13 different ports around the U. S. and the Port of Portland had the highest percentage of bulker arrivals (52.4 percent), dwarfing the bulker proportion of other West Coast ports (all less than 13.5 percent). However, concluding that Portland is at higher risk of propagule supply from bulkers compared to other ports is tempered by the actual numbers of arrivals – for instance, the 9.2 percent of bulkers that contributed to LA/Long Beach arrivals was still 237 bulkers more than Portland received during the same period.

Frequency of repeat arrivals and donor regions varied greatly between vessel types which has implications for the frequency, duration, and geographic source of inoculation. Scale is a consideration; duration of propagule supply from hull fouling refers to the length of time an individual hull remains a potential donor (days) while frequency refers to the repeated delivery of the same propagules (months/years). With this in mind, the combined threat of long port durations and a high proportion of visits from one source region over three years provide further evidence that bulkers pose a serious threat of hull-mediated inoculation of the LCR. Despite arriving from 50 widespread countries, almost 86 percent of foreign bulker WSA arrived from the Asian/Northwest Pacific coast. However, arrival frequency of individual bulkers was low – 57 percent were one-time visitors. On the other end of the spectrum, barges had a high frequency of repeat visits, but the majority were sourced from coastal voyages. The evidence suggests bulkers provide a high theoretical supply of transoceanic propagules on many different vessels whereas the threat of inoculation from barges stems from more regional supply of high density (because of slow movement) and high frequency propagules.

The Northwest and Northeast Pacific coasts dominated donor regions of potential hull colonizers across all vessels, and this broadly corresponds with the overall native range of established NIS in the LCR (Sytsma et al., 2004). The established invaders may have come directly from their native ranges or as a secondary introduction from an already established population on the U.S. Pacific Coast. Due to a lack of information on the relative fouling loads of coastal versus transoceanic voyages on the U.S. Pacific Coast, it is difficult to conclude whether primary or secondary introductions to the LCR have been

more common and are more likely. Nonetheless, studies elsewhere of hull fouling on regional versus transoceanic vessels suggest that heavier fouling loads are more common on regional vessels because of less stressful, shorter voyages (Visscher, 1928; Skerman, 1960; Coutts & Taylor, 2004). Some of this evidence may be confounded by changes in latitude. Vessels traversing longitude rather than latitude may pass through fewer environmental stresses and consequently retain more fouling biota.

Regardless of distance and direction of travel, a large number of previous ports of call suggest a greater pool of potential invaders. The broad geographic scope of last ports-of-call for vessels arriving to the LCR highlights the global scale of potential introductions to the system. Minchin & Gollasch (2003) presented a similar figure outlining the ports visited and thus the worldwide nature of the threat that a single vessel can pose. Clearly from one arrival - with its own geographic and operational history - to the next, a highly disparate risk of inoculation is absorbed by the recipient waters. In response to such an unpredictable source of potentially detrimental aquatic invaders, different regions have targeted certain species for extra attention based on vector and impact criteria (e.g. Hayes & Sliwa, 2003). Such an approach is useful but relies heavily on the history of known spread and impacts of the most 'visible' species. Control at source regions is impractical because of the sheer numbers of potential inoculants, so controlling at the vector stage is more achievable and desirable (Puth & Post, 2005).

Wonham & Carlton (2005) have recently examined the patterns of marine invasions in the Northeast Pacific, focusing on four major estuaries: Puget Sound, Willapa Bay, Coos Bay and Humboldt Bay. For the whole region, 21.9 percent of NIS were solely shipping-mediated with 8.1 percent attributed to hull fouling. In the LCR, shipping was considered solely responsible for transferring 39.5 percent of established NIS and hull fouling was not considered the sole vector for any NIS (although hull fouling may have contributed 9.8 percent but could not be decoupled from other possible mechanisms [Sytsma et al., 2004]). The shipping-mediated proportion of NIS in the LCR would increase if certain unqualifying taxa (e.g. freshwater plants and mammals) that were discounted in the regional analysis were removed. Based on shipping tonnage, Puget Sound had fewer shipping-mediated invaders than would have been predicted from

shipping traffic whereas the converse was true for the other three estuaries (Wonham & Carlton, 2005). Thus, (as a qualitative comparison) the LCR, with a similar number of vessel arrivals as Puget Sound (MARAD data) but with a higher proportion of shipping-mediated invaders, may also have a higher proportion of ship-mediated introductions than shipping alone would predict. This would counter the trend for the region as a whole; higher organism retention with subsequent establishment were viewed as reasons for the three coastal bays having better correlation with ship-delivered propagule pressure than Puget Sound (Wonham & Carlton, 2005). With high flow and flushing rates, the LCR does not share the water and organism retention times that were considered important for the three coastal bays.

Numerous previous studies have used vessel arrivals or some other proxy (tonnage) as an indicator of propagule pressure between recipient regions (port systems, e.g. Drake & Lodge, 2004; Niimi, 2004; Wonham & Carlton, 2005). Although at a coarse level more shipping means more opportunity for shipping-mediated propagules, this approach has been demonstrated to be unsuitable for ballast water analyses because it fails to characterize the variability in propagule density and magnitude between vessel types, receiving ports, and voyage routes (Verling et al., 2005). The same may be true for the hull fouling vector, but perhaps to a lesser extent. For example, the mean WSA for barges in the LCR is half that of bulkers, containerships, and tankers. Giving equal weighting to all vessel types may not encapsulate the variability in size that may influence propagule delivery. Despite the lack of data for some factors, hull fouling also probably differs in density, magnitude, and frequency between vessel types, receiving ports and voyage routes. The reason arrivals and tonnage data may be more closely correlated with hull fouling propagule pressure than ballast water is because the variability in potential ‘discharge’ of propagules is more tightly coupled to the external ship vector rather than the internal one. Overall, however, modeling of shipping vectors and their risk of inoculation requires an examination of the inherent variability across ship types, sources, routes, and recipient waters.

4.2 Hull fouling density

As was the case with most other studies of hull fouling, too few vessels ($n=10$) were sampled during this project to allow firm conclusions on the extent and composition of fouling biota entering the LCR across different vessel types. It is clear, however, that vessels are delivering propagules to the region via hulls with varying densities and frequencies. All vessels examined, including those by archival video footage, had some biota associated with their hulls. Evidence of biota on certain vessels amounted to just a few individuals (denoted by less than one percent), but a 'sterile hull' (from a macro-fouling perspective) was not encountered. Throughout the hull fouling literature, vessels devoid of biota are in the minority (examples of zero biota can be found in Visscher [1928], Coutts [1999] and Ruiz, Brown, Smith, Morrison, Ockrassa & Nekinaken [2004]), although this may reflect a bias in reporting 'negative' results. Nevertheless, if it holds true across the board that a small minority of vessels have no fouling, then the threat of inoculation from vessel arrivals to the LCR, and other ports, is significant.

For vessels sampled on drydock, there was much variability in terms of type, voyage route, and hull husbandry, and this was reflected in the biotic variability between vessels. The six vessels that had low fouling levels (less than 20 percent) were either frequent visitors to the LCR (barges) or appeared to have had relatively recent hull maintenance (dredge and bulker). Combinations of regular and lengthy exposure to freshwater and fairly fresh anti-fouling paint appear to reduce or maintain levels of biofouling to a minimum. The extent of biofouling was low on these vessels and the number of species was also limited to three or fewer taxa. These taxa are probably all native to the region (and probably to the LCR) with the possible exception of the biota attached to the bulker; further taxonomic resolution of the hydroid found on this ship is required to determine its biogeographical (native) status.

The four vessels that were heavily fouled had either never visited the LCR in recent times (cutter and tanker) or were resident within the system (lightship and passenger). All of these vessels had very high percentages of their underwater surfaces covered in biota, but the passenger vessel did not have a correspondingly high number of species. The major difference between it and the lightship was that it spent more time moving during recent

months and therefore only algae settled to its hull. In contrast, the lightship had a number of entirely LCR-derived biofouling taxa. Interestingly, two of these species, *B. improvisus* (barnacle) and *F. indica* (bryzoan) have been introduced to the LCR suggesting that secondary spread on vessels within the system may be important. A high density of tube-dwelling amphipods (*Americorophium* spp) were also found on the hull which may indicate that floating structures and visiting vessels act as novel substrata for numerous fouling and motile taxa. In contrast to these two vessels that were relatively small, the two large vessels with substantial fouling arrived with a significant nonindigenous propagule supply. The overall extent of cover and species richness for the cutter were 80 percent and 12 respectively, and for the tanker 60 percent and 14. These percentages equate to 1612 m² and 5204 m² of fouled surface area for the cutter and tanker, respectively. Even though much of this area was covered in a thin layer of green algae, the high numbers indicate that the drydocking of these vessels was overdue. Organism densities for certain taxa in certain areas (e.g. tubeworms on the keel of the cutter) were also notably high, and if zooids within colonies are considered as well as individually settled algal spores, then the numbers of individual propagules delivered by these vessels must have been of the order of tens of thousands. Moreover, although further taxonomic resolution is required for numerous taxa, all of these propagules were nonindigenous to the LCR and surrounding coast because the vessels were visiting from overseas for the first time in years (or ever). Even if the species were native to the region, their populations were not, and it has been argued that such below-the-species-level introductions are also undesirable (Turon, Tarjuelo, Duran & Pascual, 2003).

Density of organisms varied by location on vessels in general concordance with previous studies (Coutts & Taylor, 2004 and references therein). Recesses and heterogeneous areas of the hull, such as intake gratings, rudders and propellers, were commonly fouled, sometimes heavily. Waterlines were the most commonly fouled, simply because algae take advantage of high light levels and possibly reduced anti-fouling capabilities. Patterns of biofouling distribution within drydocking support strips were pronounced on two vessels; one (bulker) only had fouling below the waterline within the strips and the other (cutter) had clear differences in density between adjacent areas inside and outside of the strips (see figure 16). Ruiz et al. (2004) found biota within drydocking strips but

not to the extent that was found elsewhere on vessels in New Zealand (Coutts & Taylor, 2004). The present study also determined that on the heaviest fouled vessels, organism density and composition within and outside the strips can reach a level where differences between the two no longer exist. This was noted for the lightship and tanker, where the supports for the current drydock were not placed on precisely the same spot as previously and organism coverage was so extensive that any original differences in species accumulation or succession had been overcome through time. However, this feature is probably restricted to very few commercial vessels.

All but one of the vessels examined by video footage had consistently minimal levels of fouling. The one vessel that was substantially covered had significant algal growth because of a long lay-up period. It could be argued that the data for the other six vessels is more representative of the commercial fleet than the drydock data because these vessels were not at the lowest end of the spectrum in terms of inter-drydocking period. If so, propagule pressure from hulls may be much less, and much less variable, than the drydocking vessels indicated. However, once again there are far too few replicates on which to base such a conclusion.

It would be worth investigating the distribution of vessels in terms of the time since last drydock. It is unknown whether this would approximate a normal distribution with fewer vessels at the extremes and many vessels at intermediate levels. Coutts & Taylor (2004) used archival footage to analyze hull fouling on 30 vessels in New Zealand. It appears from their analysis that the footage was taken in a more structured and standardized way compared to the vessels examined here, allowing for quantitative comparisons between vessels. It also appears that the vessels in New Zealand had a greater extent and number of species on hulls than were found in the LCR, possibly because the New Zealand vessels were considered to be at the lower end of the hull maintenance spectrum for commercial vessels. Although video footage is a cost-effective method of examining hull fouling (possibly of more representative vessels in the fleet), when the purpose of the original survey does not include biofouling estimation, it is likely to be of limited use because of the haphazard way the sampling area is covered.

The potential for reducing hull fouling with periodic exposure to freshwater in the LCR is unclear. As a potential donor of propagules, the LCR also has a wide distribution of next ports-of-call – 273 ports in 47 different countries. Coastal departures were evenly distributed between the home and adjoining bioregions (33 percent each). Foreign departures from the LCR were primarily (75 percent) about to undertake transoceanic voyages to the NW Pacific. The possibility of freshwater taxa surviving such a voyage is negligible. In fact, as a node of shipping, the benefits of lethal changes in salinity to marine fouling taxa may be felt beyond the Columbia River. Other ports with regular links to the LCR are likely to benefit from reduced propagule pressure as a result of the lethality of the LCR to marine organisms. There are three notes of caution however.

First, two previous studies of LCR-departing vessels (one each on a coastal and overseas voyage) have cast doubt on the efficacy of freshwater ‘purging’ of organisms from hulls. While examining the different legs of a voyage by a sailing vessel from Oregon to San Francisco, Carlton & Hodder (1995) found 60 taxa, all but one of which were assumed to have recruited to the hull subsequent to departure from the LCR (after a 35-day stay). However, it is possible that numerous taxa may have settled to - or remained on - the hull during its time in the LCR (e.g. numerous crustaceans, annelid worms, and chironomid larvae). Similarly, Brock et al. (1999) examined the USS MISSOURI before and after a nine-day stay in the LCR. They counted 116 live taxa on the hull in Puget Sound prior to its departure and 12 (alive) on its arrival in Hawaii. A subsequent study of this vessel revealed that mussels nonindigenous to Hawaii successfully reproduced and colonized another vessel in Pearl Harbor (Apte et al., 2000). Although it was deemed an efficient and cost-effective method of preventing species transfers, it is clear that exposure to LCR waters did not remove all organisms from the hull or perhaps prevent some new ones colonizing.

Second, invasions that have established in the LCR and other estuaries include euryhaline taxa that may have arrived via hulls. There were eight taxa listed in the LCRANS survey as established NIS that may have been introduced via hulls; all share a wide tolerance of salinity (see Sytsma et al., 2004). Clearly, sharp reductions in salinity do not make a

recipient region immune from introduction via hull fouling, but the population of potentially successful propagules is smaller than for fully marine habitats.

Third, any benefit of reduced propagule pressure to other ports from hulls that have been ‘treated’ by freshwater in the LCR may only be short term. Many fouling organisms may not necessarily be removed from a hull despite mortality. The remaining (usually hard) body parts may act as a very suitable substratum for further biofouling – a type of post-mortem facilitation – that may ultimately result in a larger propagule population than would otherwise have been on the hull. Floerl et al. (2005) found that in-water cleaning had a similar effect; the remaining debris of species physically removed from panels provided more suitable substratum than untreated panels. Thus, the NIS donor potential of the LCR is complex, combining factors that advance and hinder propagule spread.

4.3 Environmental receptiveness to hull propagules

Propagule quality, environmental tolerance, and habitat suitability are key components of establishment once a vector has reached its destination. The LCR has an enormous discharge of freshwater entering the NE Pacific Ocean. Consequently, salinity, flow rates, and habitat availability are limiting factors to marine fouling organisms that are attached to hulls entering LCR ports. The benthos of the LCR is sedimentary and substratum stability is an important feature in resource utilization by sessile fouling species. Increases in flow rates may also dislodge certain taxa from hulls causing them to rain down on unsuitable (soft) substrata. However, salinity is probably the most obvious limiting factor, which only broadly tolerant species can withstand. Not only is the change in salinity a factor in reducing the probability of inoculation, but the rate of change must also be important. Experiments with ballast water organisms have shown that the rate of reduction in salinity, rather than the absolute change in salinity, causes mortality in certain taxa (Verling, pers. comm.). Thus some propagules entering estuaries on a hull may be able to survive if the gradient of salinity change is long. This is unlikely in the LCR because it is a salt-wedge estuary and the change from marine to freshwater conditions occurs within minutes of entering the system.

Analysis of assemblages through the more than 200 km stretch of the LCR indicated that there was little differentiation in species composition. Although the multivariate ordinations used only presence-absence data, it appears that the effects of conditions such as flow and salinity are fairly constant throughout the lower portions of the river for both benthic and planktonic communities. Within the estuary, settlement rates on panels varied greatly based on local water retention. Further examination is required, however, because the panel data was confounded by a fixed vs floating setup. The panels did show, however, that some established invaders (*e.g. C. lacustris*) can dominate structures and may be pests of aquaculture and boating throughout the region. As settlement intensity was low, no competitive interactions on panels were observed and further study is required to enumerate the fouling taxa of the estuary and evaluate their competitive abilities.

On arrival to the LCR, population dynamics and reproductive ecologies of propagules are important factors in successful inoculation. An Allee effect (Allee, 1931), or minimum population threshold, must be achieved for a population to recruit successfully. On a vessel hull, proximity and density of propagules are an obvious manifestation of this threshold. If propagules are too few or too far apart (below the threshold) then the probability of successful spawning and recruitment is zero; if the reverse is true then initial recruitment is likely (Grevstad, 1999). This has implications for propagules arriving to the LCR. If changes in salinity and temperature are cues to spawning (Minchin & Gollasch, 2003), the mouth of the LCR may be an area at high risk of inoculation by NIS. High density on a hull would be an important prerequisite of any successful inoculation in this area because quick flushing times would probably negate the effect of repeated inoculations. However, the risk of repeated inoculations should not be discounted since this area is also the recipient of frequent ballast water discharges. Since organisms have life stages that occupy both sub-vectors of shipping, then it is not unlikely that ships carry both life stages of individual species at the same time. Thus, higher salinity and high densities of propagule supply (through frequent de-ballasting and cues to spawning) mean that the mouth of the river may be the area most at risk from introductions resulting from shipping.

5. CONCLUSIONS

The relative threat of NIS introduction to the LCR from hull fouling is probably lower than for other Pacific coast ports. This is not necessarily because of lower propagule pressure – if anything the magnitude, frequency and origin (geography) of vectors (WSA data), and the preliminary data on hull fouling extent presented here suggest that delivery of propagules is not a limiting factor. The acute reduction in salinity and subsequent lack of suitable habitat are more than likely major limiting factors. In the same way that marine species would not survive such a change in salinity in the LCR, freshwater species from other ports would not survive the oceanic portions of their journeys and for this reason, the LCR is probably a useful node of shipping for other ports as it prevents many NIS from spreading via hulls. The threat from ballast water, although limited by the number of donor freshwater ports, may be more significant and have an additive effect on the risk from hull fouling. A number of shipping-mediated introductions have already become established in the LCR, which indicates that the LCR is not immune to nonindigenous propagules. As a potential donor of NIS, the LCR may also be a lower risk than other Pacific coast ports. High mortality coupled with low recruitment on vessel hulls in the LCR may reduce the propagule pressure of outgoing vessels to other ports. This benefit may only work over the short term though, because facilitation may actually increase the threat of NIS translocation in the longer term.

The factors involved in structuring hull fouling assemblages are numerous. Determining their relative importance and how they interact will take a much larger sample size than most (maybe all) hull fouling studies to date. One major advantage, however, is that hull fouling research can build upon research into the other shipping sub-vector - ballast water. Analyses of organism concentrations in ballast water studies sometimes have large sample sizes (e.g. $n > 795$, Carlton & Geller, 1993; $n = 354$, Minton et al., 2005), include substantial discharge data for different vessel types (Verling et al., 2005), and take account of shipping data over large spatial and temporal scales. This provides key information on propagule density, magnitude and frequency. Even on a global scale, estimates have been made about the number of organisms being transported on a daily basis in ballast water (7000 – 10000 species [Carlton, 1999]). No such estimate has ever

been attempted for hull fouling, primarily because there is not enough data to begin even a crude calculation. Over the entire population of vessel arrivals for this study, a sample size of 1 percent would involve examining 58 hulls - more than most sample sizes in the literature. If the threat that the hull fouling vector poses to the LCR and other coastal regions is to be critically evaluated, then a large number of replicate vessels must be examined to determine density, magnitude and frequency of propagule supply.

At present, hull fouling management strategies to prevent introductions focus heavily on the density component of the fouling vector (*e.g.* Godwin, Eldredge & Gaut, 2004). This approach is effective because a heavily fouled vessel has huge potential to inoculate an area as organisms are generally numerous enough, and in close enough proximity, to act as a successful founder population. Once a certain threshold of density within a species is surpassed (Allee effect), the likelihood of establishment is high (Grevstad, 1999). Preventing this type of potent inoculation is highly desirable, readily detected, and relatively easily implemented. However, this management approach ignores the complex interaction of magnitude, frequency and duration of propagule pressure from hulls. The possibility that an introduction can occur because of the arrival of numerous vessels with the same species (a dripping-tap inoculation) rather than just a single large inoculation by one vessel (flood) is rarely considered. Until better data are available to quantify this type of threat, high density propagule supply will remain at the forefront of management strategies but the cumulative threat from within - and between - ship types and donor regions will remain.

5.1 Further research and monitoring

Monitoring for marine fouling species at upriver ports such as those in the LCR, using panels or direct surveying of dock sides, may not prove an efficient use of resources. Although certain taxa have managed to establish themselves, constant monitoring would not be commensurate with the threat posed by marine species transferred on the external surfaces of ships. A better method for the LCR may be to focus on certain taxa that require special attention (as is being carried out for the zebra mussel and mitten crab) and carry out the LCRANS survey at regular five-year intervals. Repetitive re-sampling of the LCR using LCRANS as a template would be beneficial for four reasons. It would: 1)

allow monitoring of new introductions from multiple vectors; 2) provide useful data on the relationship between potential propagule supply from different vectors (hull fouling) and successful establishment; 3) permit assessment of the changing status of already established NIS; and 4) provide a measure of how well preventative and eradication methods are progressing. Using settlement panels at the mouth of the river in areas where salt water intrudes into the estuary may be more useful because: 1) this is a site where environmental conditions are more favorable to marine species; 2) spawning may be induced by changes in depth, temperature and salinity; and 3) de-ballasting occurs as ships cross the bar and vessels at anchorage are common, i.e. the frequency and duration of propagule supply is great.

A method of assessing the maintenance condition of vessels arriving (time since last drydock) would be useful for determining risk of inoculation for different vessel types or specific ports. A template already exists in New Zealand where the Ballast Water Declaration Form includes a section on hull maintenance (i.e. last drydock, laid-up time, maintenance plans while in port). It does not appear that this data collection would impose a new significant addition to the paperwork for ship operators because the questions are asked in such a way that the same answer (e.g. date of last drydock) remains the same for long periods. This type of information would allow the inclusion of a further important factor in the analysis of potential propagule pressure.

Future research on hull fouling in the LCR should be part of a broader framework for the North American Pacific Coast because of the inter-connectedness of the entire region in terms of shipping ‘vectors’ and port ‘nodes’. Such a framework would allow quantitative analyses of the effect of port on vessel type and propagule delivery; the flux of potential magnitude (or WSA) between ports; and, most importantly, a comparison across vessel types of the extent of fouling arriving to the U.S. West Coast on ships’ hulls. From a quantitative perspective, much more data are required to answer the basic questions regarding the extent and composition of fouling on commercial vessels and WSA arriving to each port. It is also important that each vessel examined is characterized sufficiently (hull area sampled); previous studies with large numbers of ships sampled may not have had adequate sampling coverage per vessel (e.g. 30 cm², Gollasch, 2002).

Experimental data are required on the survival and fate of marine organisms subjected to acute drops in salinity. The short-term benefit of visiting riverine ports, such as the LCR, is that most organisms would be expected to die (with few new recruits) so the benefits of such ‘treatment’ of hulls will spread beyond this port to next ports-of-call. Over the longer term, however, if the hard parts (calcareous shell material) of organisms killed by freshwater immersion remain on the hull they may prove a more biofouling friendly substrate and lead to higher levels of fouling than would be expected if the secondary substratum were not present. Experimental studies of the interaction between propagule pressure and rates of establishment, relating specifically to hull fouling, are also required if future management strategies are to be successfully implemented. In particular, testing between the relative importance of propagule supply (density) and frequency in successful introduction of fouling organisms needs to be carried out.

6. RECOMMENDATIONS

Fouling as a source for NIS is not well studied. As seen from this initial effort to characterize and quantify hull fouling as a source for NIS in the LCR, the potential for transport can be very large. For future NIS research, it is therefore important to develop a logical approach to determining fouling extent and risk from introductions from ships.

- Researching new areas for contributions of NIS from fouling should begin with the WSA approach. The WSA approach can provide an overall estimate of potential fouling by organized classes of ships. The classes of ships can be defined for the specific area and can include small boats as well as large commercial vessels. Seasonal patterns and class distributions can be discerned from the data prior to actually surveying ships’ hulls.
- Background information could be gathered from ships by requesting data about hull management in the reports currently required for ballast water management notification reports. Information such as time since last drydock, hull protection method, and last/recent ports of call can be combined with the WSA information to describe the distribution of fouling risk to an area. Review of New Zealand’s assessment approach would be useful.

- Physical assessment of hulls is required to characterize and document this mode of NIS transport. Assessment can range from visual evaluations from above the waterline to video imaging of the overall hull and areas of interest to detailed inspection and quantitative sampling during drydocking.
 - Evaluation criteria and plans should be investigated and standardized. The actual areas of significant fouling may only be a small proportion of the WSA, thus “percentage fouled” may not be a valuable metric for characterizing hulls.
 - The potential for the use of remotely operated vehicles (ROVs) should be investigated. ROVs can be used in situations too difficult or dangerous for divers.
 - Adequate sample sizes should be determined for lightly fouled and heavily fouled areas.
 - Surveys of hulls should include sea chests, bow thrusters, and all other cavities or potential hot spots for fouling.
- For selected species of interest, lab-scale tests of responses to salinity and changing salinity regimes should be conducted to provide an estimate of the species’ survival/invasion potentials.
- Invasion potential should be investigated in terms of high density exposure (as from highly fouled hulls) and frequency of exposure (as from multiple inoculations).
- Small boats should be included in hull fouling investigations as they may play heavily in frequency of exposure/multiple inoculations risks.

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